Final Report

DETERMINATION OF ENGINEERING PROPERTIES OF WASTE SALT FOR BACKFILLING IN UNDERGROUND POTASH MINES

by

Richard J. Beddoes
RE/SPEC Ltd.
Calgary, Alberta

September, 1984

8 pp

Work on this project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources, Canada.

DSS File No.:	26SQ.23440-3-9205
DSS Contract Serial No.:	OSQ3-00255
CANMET Project No.:	310104
CANMET Scientific Authority:	M. Bétournay
RE/SPEC Ltd. Report No:	RSL-004

MICROMEDIA

EXECUTIVE SUMMARY

In order to control underground deformations and surface subsidence, potash mine operators in Saskatchewan are considering the use of salt tailings for backfilling mined-out rooms. As part of the feasibility assessment for this approach the consolidation behaviour and strength development of salt tailings under strata pressures up to 25 MPa have been studied.

Crushed salt tailings from Rocanville mine, Saskatchewan, were used for a series of tests designed to study the relationship between moisture content, consolidation behaviour, and strength development under quasi-static and constant load (creep) conditions. Additional tests were performed to characterize the crushed salt and to aid in the interpretation of results.

For a given compactive effort it was found that the density of unconsolidated tailings increased with increasing moisture content but that the dry density following quasi-static consolidation to 25 MPa axial load was independent of moisture content. The short term creep rate under constant loads of 7 MPa and 25 MPa was also independent of moisture content. Creep consolidation over extended periods of time was only studied using an initial moisture content of 5%; however it appears unlikely that creep behaviour is altered significantly by higher initial moisture contents because, in the short term tests, specimens drained to a moisture content of about 3% within a few minutes.

Post-consolidation strength is apparently dependent upon inter-grain bonding formed during consolidation. This in turn is dependent both upon the length of time over which the load is applied and the maximum value of the load. Negligible unconfined strengths result from quasi-static compression, even at stresses as high as 35 MPa, but strength develops quickly under creep conditions. Under a stress of 25 MPa, unconfined strengths of over 10 MPa resulted from creep consolidation of one week duration, and it is probable that strengths at least equal to those of a solid salt core would eventually be achieved. Microscopic study indicated that grain boundary creep occurs under load and that some salt recrystallization occurs at grain contacts.

Triaxial compression tests on salt which had been quasi-statically consolidated indicated that at low confining pressures it behaves as a frictional material with very low cohesion but that under higher confinement there is no frictional component to strength and the Mohr's envelope follows a line of constant shear stress.

This study has shown that a strong backfill material can be formed from crushed salt following 30 to 35% consolidation. Moisture content is only important so far as it affects the density at which the tailings can be stowed and the amount of brine which must be removed as they consolidate. Considering, also, that the backfill will not be stowed tight to the roof of the room a total closure of 45% of the room height is anticipated.

Creep consolidation has been identified as the most important mechanism in strength development and it is recommended that this aspect should be studied in greater depth to provide information about the long term behaviour of consolidated tailings.

COMPTE-RENDU DE LA DIRECTION

En vue de maîtriser les déformations souterraines et les affaissements de la surface, les exploitants de mines de potasse en Saskatchewan envisagent l'utilisation de résidus de sel pour le remplissage des chambres dont le minerai a déjà été extrait. La praticabilité de cette méthode a été évaluée jusqu'à maintenant, par des études sur le comportement de la consolidation des résidus et sur le développement de leur résistance sous des pressions de couches géologiques pouvant atteindre 25 MPa.

Des résidus de sel concassé, provenant de la mine de Rocanville en Saskatchewan, ont été soumis à une batterie de tests afin d'étudier les relations qui pouvaient exister entre leur teneur en humidité, leur comportement lors de la consolidation, ainsi que le développement de leur résistance, sous des conditions de pressions constantes (fluage) et quasi-statiques. Des essais additionnels ont été exécutés afin de découvrir les caractéristiques du sel concassé et faciliter ainsi l'interprétation des résultats.

Lorsqu'on applique une force de compression donnée, la densité des résidus non-consolidés augmente avec la hausse d'humidité mais par contre la densité à sec, suivant une consolidation quasi-statique sous une charge axiale de 25 MPa, s'avère complètement indépendante de la teneur en humidité. Sous des pressions constantes allant de 7 MPa à 25 MPa, la vitesse de fluage à court terme est également indépendante de la teneur en humidité. La consolidation du fluage s'étendant sur une plus longue période n'a été étudiée qu'avec une teneur initiale en humidité de 5%; toutefois, il semble improbable que le comportement du fluage soit affecté d'une façon significative par une plus haute teneur initiale en humidité car les tests effectués à court terme révèlent que la teneur en humidité des échantillons s'abaisse d'elle-même à 3% en quelques minutes.

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Cette étude démontre que l'on peut obtenir un excellent matériel de remplissage à partir du sel concassé et consolidé de 30 à 35%. La seule importance de la teneur en humidité réside dans le fait qu'elle influence la densité à laquelle les résidus peuvent être entassés et la quantité de saumure qui doit être enlevée au moment où ils se consolident. De plus, comme le remplissage ne se fera pas jusqu'au plafond de la chambre, on prévoit une fermeture totale de la chambre à 45% de sa hauteur.

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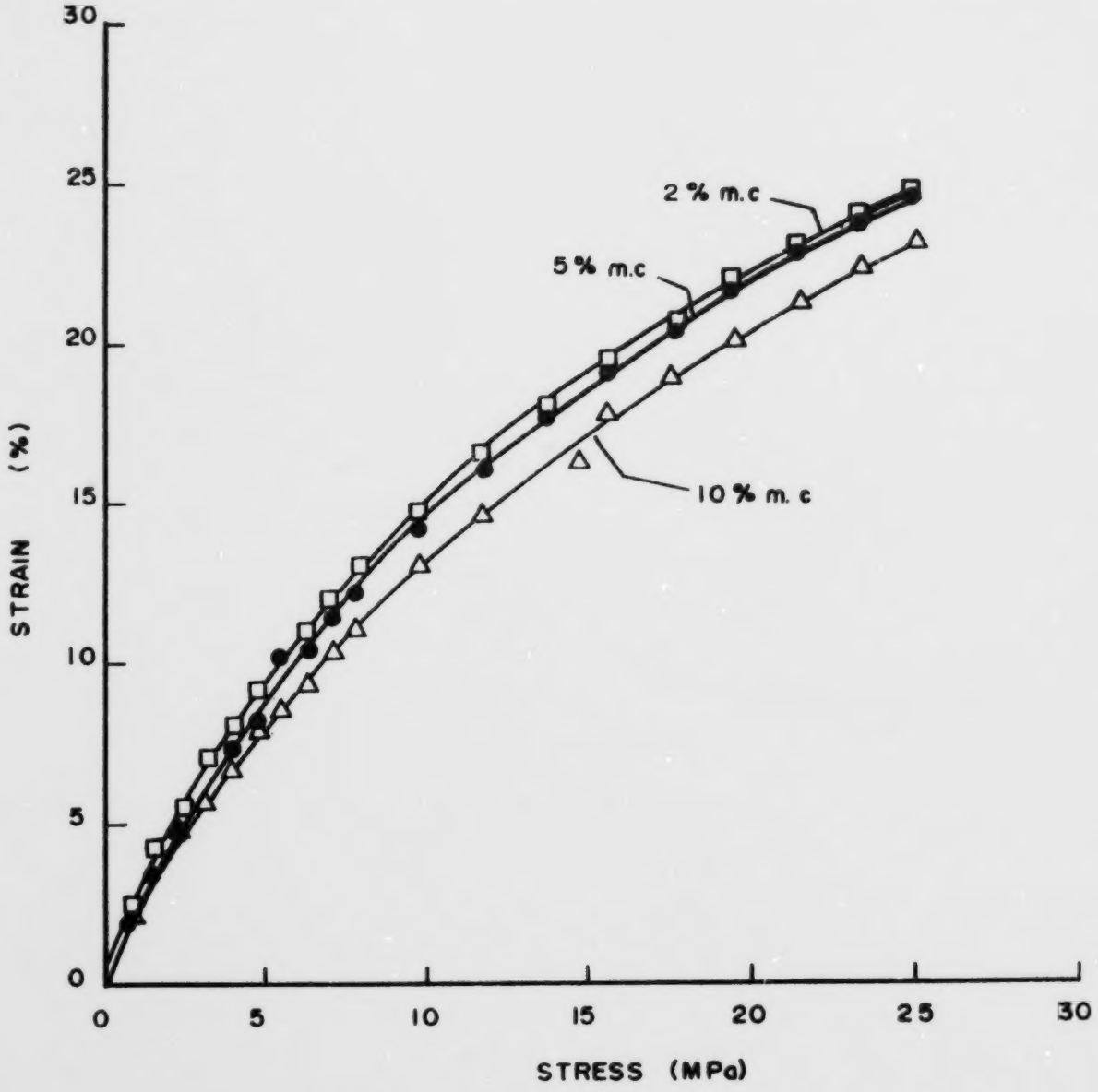

Figure 4-3. Typical Quasi-Static Consolidation Curves for Crushed Salt Tailings at Different Moisture Contents.

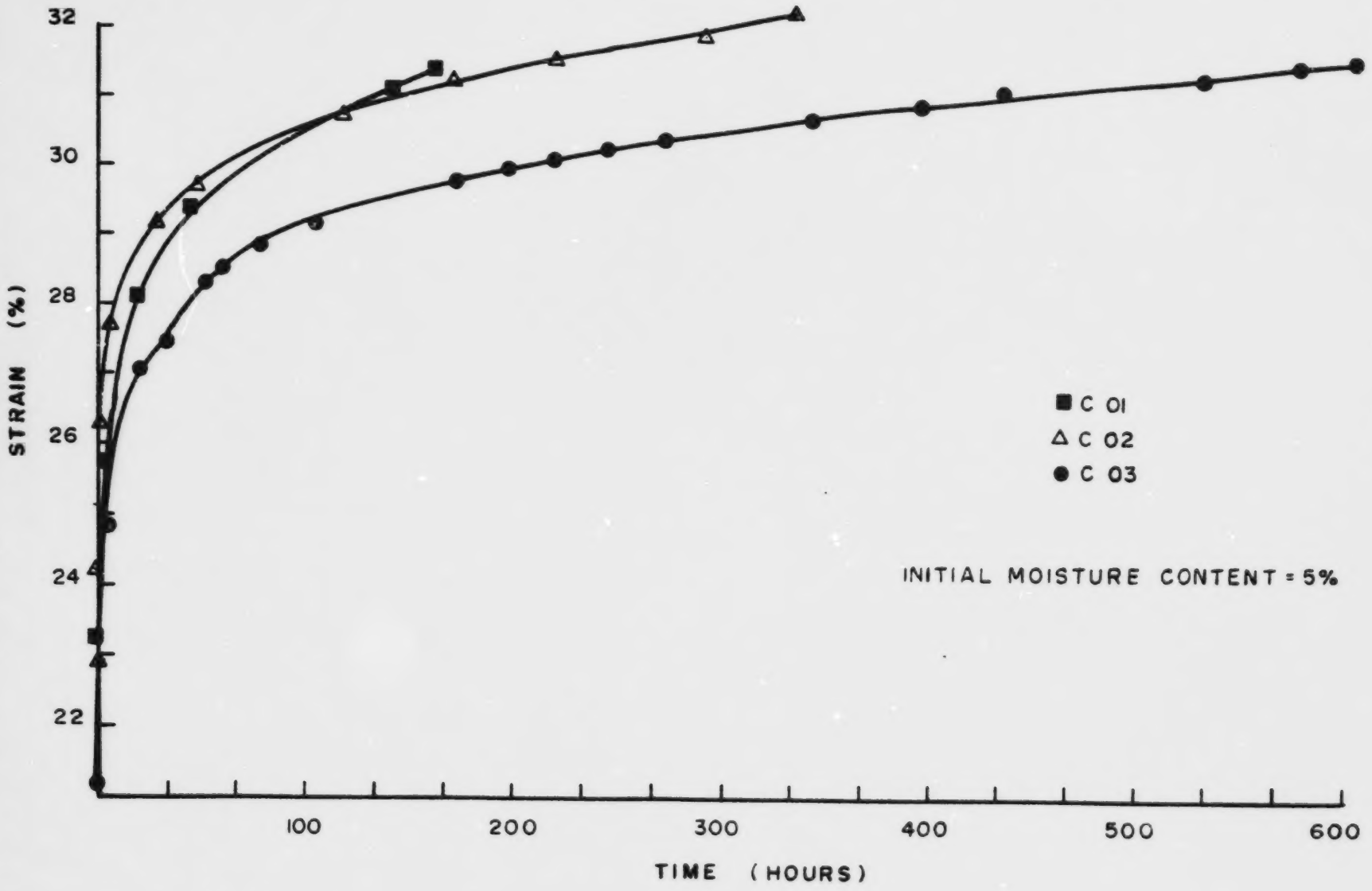

Figure 4-10. Creep Consolidation Curves for Salt Tailings at 25 MPa Axial Stress.

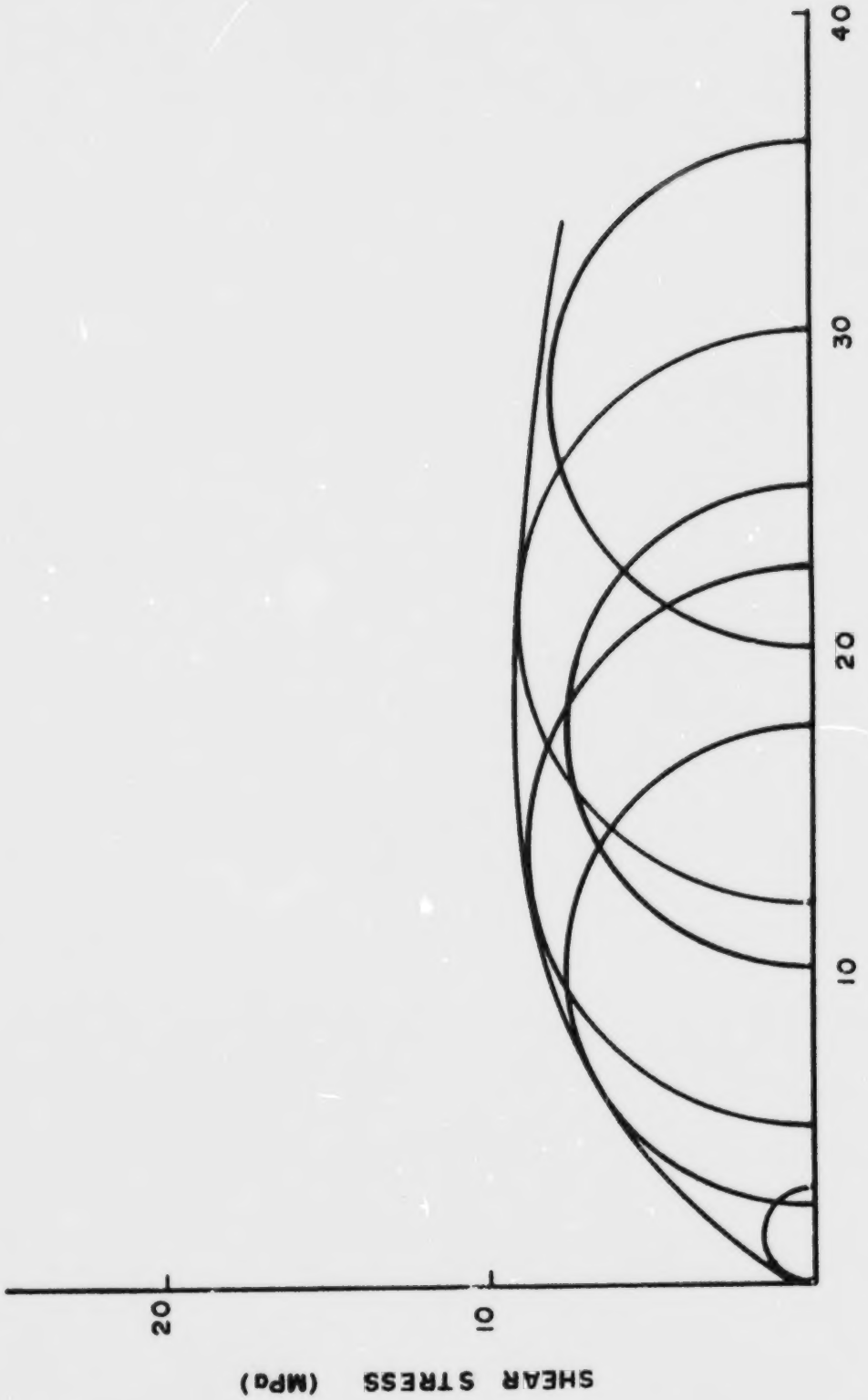

Figure 4-12. Mohr's Circles for Salt Tailings Consolidated to 25 MPa.

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ABSTRACT

Salt tailings from a Saskatchewan potash mine have been tested to establish their consolidation behaviour at various moisture contents under loads similar to strata pressures in the mining interval, where the material may be used as a backfill. The density of tailings consolidated in steel tubes to 25 MPa under quasi-static conditions was found to be uninfluenced by initial moisture content, although moisture content has an increasingly important influence at lower stresses. Quasi-static consolidation at stresses up to 35 MPa causes negligible gain in unconfined strength but strength increases rapidly under creep conditions. After 2 weeks under a stress of 25 MPa samples achieved a strength of 14 MPa and a void ratio of 12%. The study demonstrates that salt tailings can form a strong backfill material capable of reducing room closures by approximately 50%.

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1 INTRODUCTION

Potash mine operators in Saskatchewan experience several difficulties due to closure of their workings as the salt pillars left between rooms creep or fail. Flexure in overlying strata can cause fracturing, resulting in possible water inflow to the mines and in some cases, minor earthquakes. This flexure is also mirrored by settlements at the surface. The use of longwall mining techniques which are presently being considered would aggravate these problems and cause additional problems of high abuttment and face pressures. Such problems have commonly been alleviated in other mines, particularly coal mines, by backfilling with waste material.

Stowing of mined-out rooms or panels with crushed salt tailings offers several advantages to the mine operator. Salt represents over 50% of the mined volume and poses a storage problem when dumped on surface piles which must be kept stable; it must also be contained to prevent brine leakage onto neighbouring properties. From the environmental viewpoint underground disposal is a more acceptable solution. If mined-out panels are stowed with backfill there are advantages in control of abuttment pressures and reduction in surface subsidence. However, in order to assess the feasibility of using salt tailings as a backfill material their behaviour under the range of anticipated strata pressures must be known. Recognizing the paucity of knowledge in this area the Canada Centre for Energy and Mineral Technology (CANMET) awarded a contract to RE/SPEC Ltd. of Calgary to characterize some of the properties of salt tailings under high loads.

The primary part of the investigation involved quasi-static consolidation of tailings in rigid steel cylinders to varying maximum stresses and at several different moisture contents. Consolidated samples were tested in compression under uniaxial and triaxial conditions. A short series of tests were performed to study the creep consolidation of tailings at high stresses and the resulting unconfined strength of the consolidated samples. The investigation of creep is a complex and important subject and the tests performed as a part of this contract were intended only as a preliminary study.

To provide comparison with other studies and to aid in the interpretation of mechanical test data, a number of ancillary tests were performed. These included mineralogical and grain size analyses on the crushed tailings and microscopic study of consolidated, crept and solid salts. Unit weight and moisture content determinations were performed for all samples.

The following report presents results and analyses of all the tests performed and draws conclusions regarding the effects of various parameters on the mechanical behavior of consolidated tailings. In particular the role of pore water and the development of grain bonding have been more clearly understood and are discussed in some detail. The importance of a more thorough study of strength development during creep is also underlined.

2 LITERATURE REVIEW

Very little systematic laboratory testing has been done to determine the mechanical and strength properties of crushed salt. However, some data is available from U.S.A. research programs for disposal of nuclear wastes into salt formations. One facet of their research involves backfilling around waste canisters and within mine rooms with crushed salt. Although the potash industry in general has expressed interest in using crushed salt as a backfill to improve productivity, little published data is available. Presently, consideration has been given to backfilling of mined-out rooms and panels in the Saskatchewan potash industry, and a limited amount of research into the properties of crushed salt has resulted. An extensive literature search was undertaken as part of the present study and eight useful references were found. They are described below.

Hansen (1976) performed quasi-static consolidation of a coarse grained (98% > 2 mm) uniformly graded salt using 52 mm diameter rigid steel sleeves. Initial densities and moisture contents are not quoted in the reference, but samples were packed in three layers with 25 tamps of a 6 mm diameter rod resulting in a pre-test height of 100 mm. The degree of consolidation is in the range 22 to 25 percent at 25 MPa. Generally, only low strengths were developed by consolidation although one sample consolidated to 14 MPa had an unconfined strength of 2.3 MPa. The develoment of strength may be attributed to the slow consolidation rate used - typically 100 to 130 minutes to maximum load.

Hydrostatic consolidation tests were performed by Holcomb and Hannum (1982) using samples 146 mm long and 104 mm in diameter with an initial density of 1275 kg/m^3. With a moisture content of 0.5% samples loaded to 21 MPa over a period of 2.2 hours exhibited a volumetric strain of about 22%. For this duration of loading, "creep effects were largely ignored". Following the quasi-static consolidation samples would hold their form but were friable and possessed no measurable strength. Creep tests were performed on samples quasi-statically consolidated over a period of 100 seconds.

The consolidation during the creep phase (over a time of 2×10^6 seconds) was about 50% of that during the quasi-static phase. Determination of bulk modulus gave a relationship K = (450 + 107 x max consolidation stress) MPa for quasi-statically consolidating samples.

Ratigan and Wagner (1979) also performed hydrostatic tests but used a stepped load application allowing creep at each loading stage so results are not directly comparable with the present study. Also, a maximum load of 14 MPa was used. All work connected with nuclear waste storage has involved testing at both room and elevated temperatures (up to approximately 110°C). It has been concluded that moderately elevated temperatures (up to 60°C) have a negligible effect upon strength development and compaction (Holcomb and Hannum (1982), Ratigan and Wagner (1979)).

Shor et al (1981) performed consolidation tests on 25 mm diameter samples in flowing brine. Investigations were made of the permeability of consolidating salt and concluded that salt becomes effectively impermeable at a void fraction of 2%. For 1 mm crystals under a stress of 10 MPa this state would be reached in about 35 years but the time increases with the cube of the mean diameter.

Hesterman (1979) found that very wet tailings drained rapidly to a moisture content in the range of 6 to 8 percent and he performed quasi-static consolidation and creep tests at these two end values. A fine well-graded salt was loosely packed into a mold of 200 mm square cross-section. Initial densities are not reported. Samples, compacted at 35 MPa (5000 psi) and maintained at this load for 48 hours, exhibited about 48 percent consolidation. A stepped load test in which the load was increased by 3.5 MPa (500 psi) every 12 hours to a maximum of 28 MPa (4000 psi) exhibited about 40 percent consolidation. Moisture content at the end of the tests was reduced to 0.4 to 0.7 percent.

A large testing program was undertaken by Pufahl and Yoshida (1982). The primary focus of this study was the engineering properties of partially consolidated fill, although some creep tests were performed on very small specimens. Crushed salt was compacted at 6 to 7 percent moisture content to its standard Proctor maximum dry density (1600 kg/m^3) then partially dried before uniaxial, triaxial and shear box tests

were performed. The degree of drying and hence recrystallization of salt was clearly the factor determining the final strength; strength decreased exponentially with increasing moisture content. Triaxial compression tests were performed on compacted dried samples at confining pressures up to 0.8 MPa. A cohesion of 270 kPa and an angle of friction of 53° were established for this stress range.

Tests at higher consolidation stresses have been performed by Miller (1983). These were performed at high load rates (about 7 minutes to maximum load) and to maximum stresses of 35 MPa. From this series of tests, Miller concludes that the effect of temperature variation and initial sample height to diameter ratio are negligible but that some increase in consolidation is produced by raising the moisture content from 0 to 5 percent. In one test series performed at three moisture contents, the consolidation at 2.5 percent moisture content is greater than that at 5 percent, indicating that the relationship is somewhat complicated. Results also indicate that tests did not all begin at the same initial density which casts doubt on the validity of the conclusions drawn from consolidation curves.

A study of consolidation of crushed salt was recently completed at RE/SPEC Inc. in South Dakota (Pfeifle et al, 1984). The study was designed to evaluate the relative effects of grain size gradation, moisture content, temperature and time upon bulk density and unconfined compressive strength. Using two levels of each variable, a total of eight tests were conducted in which a load of 10 MPa was applied quasi-statically over 20 minutes and was then maintained for a period of creep consolidation. During creep, time and moisture content were found to be the important variables affecting bulk density. (Moisture contents of 0% and 3% were used) but in total consolidation, grain size distribution and, to a lesser degree, temperature were important. Time and moisture content were the significant variables relative to the unconfined compressive strength. It was planned to evaluate the response of permeability to changes in the variables but tests on trial samples showed that values were greater than could be measured on the available equipment. Of particular relevance to the present study, initial densities were not dependent upon moisture content for the same compaction energy; also moisture content had a negligible effect upon the density achieved during quasi-static consolidation. Future work by RE/SPEC Inc. will include a study of permeability.

Research on crushed salt behaviour has developed separately in the United States under the nuclear waste isolation programme and in Canada related to the potash mining industry. While the standards of testing in the U.S. are generally very high they are concerned mainly with testing dry salt and with lower consolidating stresses. The value of maximum stress and the presence of brine clearly influence both creep consolidation and strength development.

In Canada testing has been performed to inconsistent standards and the aims of the research have not been clearly identified. Information vital to the proper interpretation of test data has been omitted from reports and much effort has been devoted to performing tests under conditions which are of limited practical value to the industry. In summary, it appears that careful attention to existing literature and design of experiments to address problems which are specific to Canadian requirements can lead to economical solutions to the questions which remain unanswered.

3 EXPERIMENTAL PROCEDURES

3.1 MATERIAL CHARACTERIZATION

3.1.1 Mineralogy

The mineralogy of the crushed salt tailings was studied using an X-ray powder diffractometer. A representative sample was obtained from a sample of approximately 1 kilogram by a method of quartering. The representative sample of about 10 grams was ground in a mechanical mortar for 15 minutes and a sample taken to prepare a powder slide. The diffraction pattern was obtained by rotating the sample in a goniometer under cobalt radiation. Chart interpretation was performed manually. An approximate quantitative analysis was performed using maximum peak intensities. An internal standard was not employed.

The crushed salt was also viewed by a geologist in hand specimen and under binocular microscope.

3.1.2 Grain Size Distribution

A sample of 2 kg mass was taken from the shipment of salt tailings and was dried in an open tray at room temperature. Upon drying the moisture content was approximately 0.5%. This sample was then sieved on a Ro-Tap sieve shaker for 20 minutes to yield size fractions of constant weight.

3.1.3 Standard Proctor Dry Density

The maximum dry density of compacted salt tailings was found using the Standard Proctor apparatus. In this test material is packed into a 100 mm diameter steel mold in 3 layers, each layer being given 25 tamps of a 50 mm diameter, 4.5 kg mass dropped 30 cm. The test is performed at various moisture contents in order to develop a moisture-density relationship.

3.2 QUASI-STATIC CONSOLIDATION TESTS

Quasi-static consolidation tests were performed on crushed salt samples packed into a thick-walled steel tube of 51.2 mm internal diameter and 62 mm outside diameter. For the series of tests conducted to study the influence of moisture content variation, a teflon liner was used inside the steel tube reducing the effective diameter to 50.05 mm. Load was applied through a pair of close fitting pistons inserted at each end of the tube. Free drainage during the test was permitted by using porous stones between the sample and piston and machining a drainage groove on the side of each piston. This apparatus is illustrated in Figure 3-1.

Salt was packed into the tubes using 40 tamps of a rod with an end area of 5.0 cm^2. This procedure gave consistent densities in most cases, although the salt containing 10 percent moisture gave a density about 5 percent higher than samples with lower moisture contents. A dry weight of 350 g was used for all samples. Load was applied to the samples using a Wykham Farrance two-post load frame with a capacity of 100 kN. The frame operates in stroke control mode and the platten travel rate was set to 1.5 mm/minute for all quasi-static tests. The application of strata pressure to backfill would, of course, also be a closure-rate controlled process. Deformations were measured using dial gauges and load was monitored using a proving ring. Once maximum load was reached, samples were either immediately unloaded or allowed to creep under constant load for 10 minutes. Following consolidation, samples were extruded from the steel tube using a hydraulic extruder and tested for unconfined compressive strength. The moisture content of the failed sample was then determined.

Samples tested at a stress of 0.034 MPa (5 psi) were 'dead' loaded and left under load for one week while deformation was monitored by means of a dial gauge.

3.3 TRIAXIAL COMPRESSIVE STRENGTH

Samples for triaxial strength testing were prepared by consolidating crushed salt in the manner described above. To accommodate the size of the triaxial cell, the teflon liner was omitted for these tests.

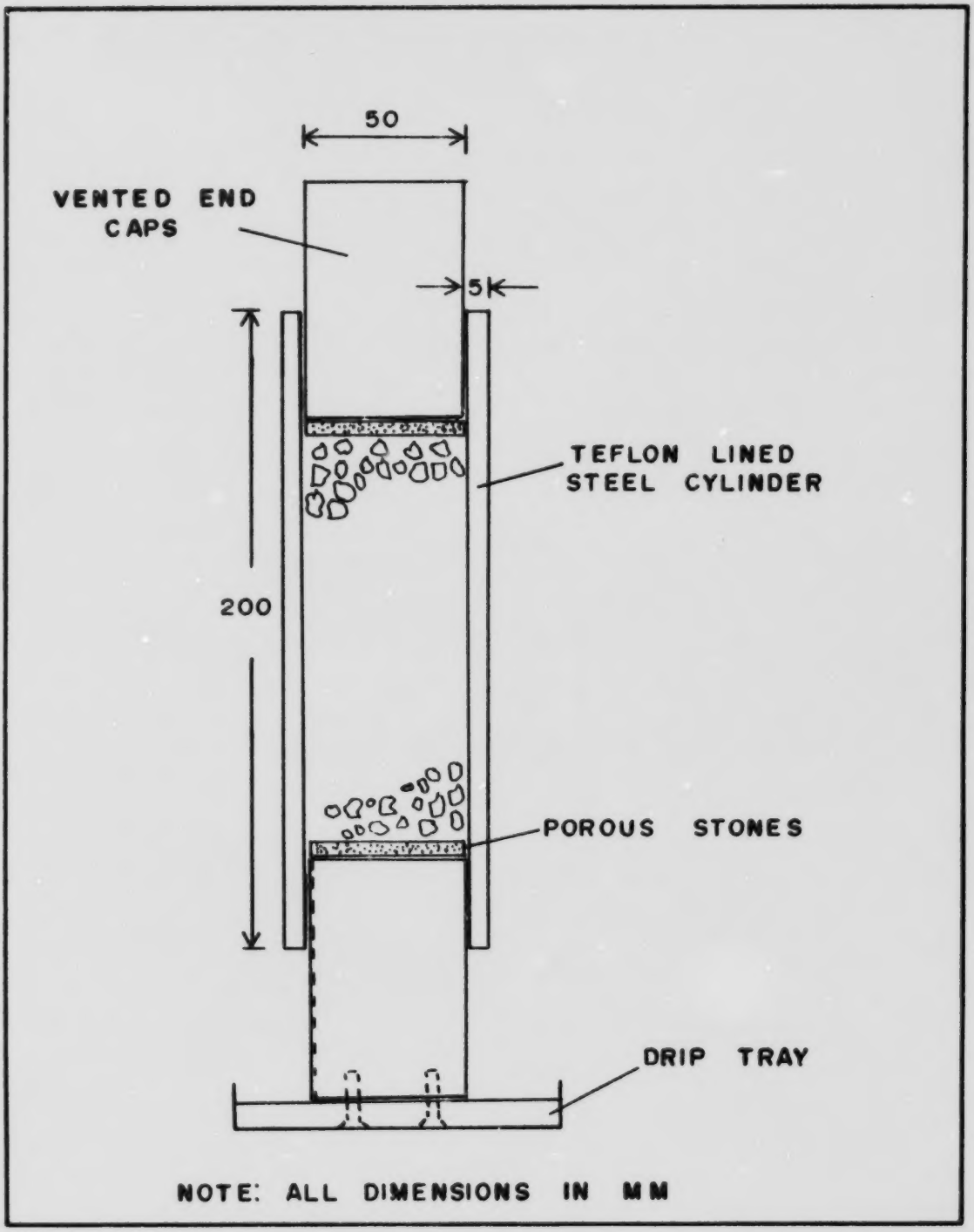

Figure 3-1. Apparatus for Confined Consolidation and Creep Testing.

Pilot tests showed that lightly greasing the steel tube resulted in approximately 1% less consolidation than corresponding tests with the teflon liner. All samples were allowed to creep for 10 minutes at maximum load in order to give them sufficient strength to withstand extruding and preparation for testing.

Confining pressure during triaxial testing was applied using a Hoek cell. The advantage of this type of cell is that samples can be changed much more quickly than if they sit within an oil-filled pressure chamber. A slight disadvantage is that the post-failure response of weak materials is affected by the containment provided by the relatively stiff plastic jacket.

Load was applied using a deformation rate of 1 mm/minute, and the tests were continued until either 15 percent strain had taken place or peak load had been reached, whichever occurred sooner. A 500 kN Reilhe load frame was used for performing the triaxial tests. Axial strain was measured using dial gauges accurate to 0.01 mm and loads were measured by a load cell connected to a digital readout.

3.4 CREEP TESTS

Crushed salt samples with a moisture content of 5 percent were consolidated in greased steel tubes of 51.2 mm diameter as described in Section 3.2. A dry weight of of 365 g was used to give the same height of compacted sample as in tests employing the teflon liner. After consolidation to 25 MPa, the samples were transferred to a hydraulic constant pressure frame. Load is applied to these small frames by air pressure acting through a pressure accumulator. Deformations were measured by monitoring movements of the load ram using a dial gauge reading to an accuracy of 0.005 +/- 0.0025 mm. The load system was housed in an environmentally controlled room at a temperature of 25°C and relative humidity of 55%.

Following periods of creep of between one and four weeks the samples were extruded, weighed, measured and tested for unconfined compressive strength. Unconfined compressive strength tests were performed on the Wykham Farrance load frame and loaded at a rate of 0.5 mm per minute.

4 EXPERIMENTAL RESULTS

4.1 MATERIALS CHARACTERIZATION

4.1.1 Mineralogy

Semi-quantitative x-ray diffraction analysis indicated that the tailings consisted of 95 to 98 percent Halite (NaCl) and 2 to 5 percent Sylvite (KCl). No other minerals were indicated. Although tailings normally have some 'slimes' content, principally clay minerals from the shale seams, we presume that much of this had been removed by the potash preparation process or washed from the portion of the tailings pile from which this sample was taken. A very small amount of red-brown clayey material adhered to the bottom of the container in which the sample was shipped but this could not be effectively recombined with the crushed salt.

4.1.2 Grain Size Distribution

The material is well graded in the size range 5 mm to 0.2 mm. It has a coefficient of uniformity (D60/D10) of 2.8. A graph of grain size distribution is shown in Figure 4-1.

4.1.3 Standard Proctor Dry Density

A standard Proctor test was performed to establish a moisture-density relationship over the range of moisture contents used in this study. The results of this test are shown in Figure 4-2. These results are similar to those reported by Pufahl and Yoshida (1982) and indicate that the maximum dry density is achieved at a moisture content greater than 10% despite the fact that brine was flowing from the sample at this moisture content. Results reported by Pufahl and Yoshida indicate that maximum density would probably be achieved at about 16% moisture content although the Proctor curve does not have its characteristic peaked form. This result is in

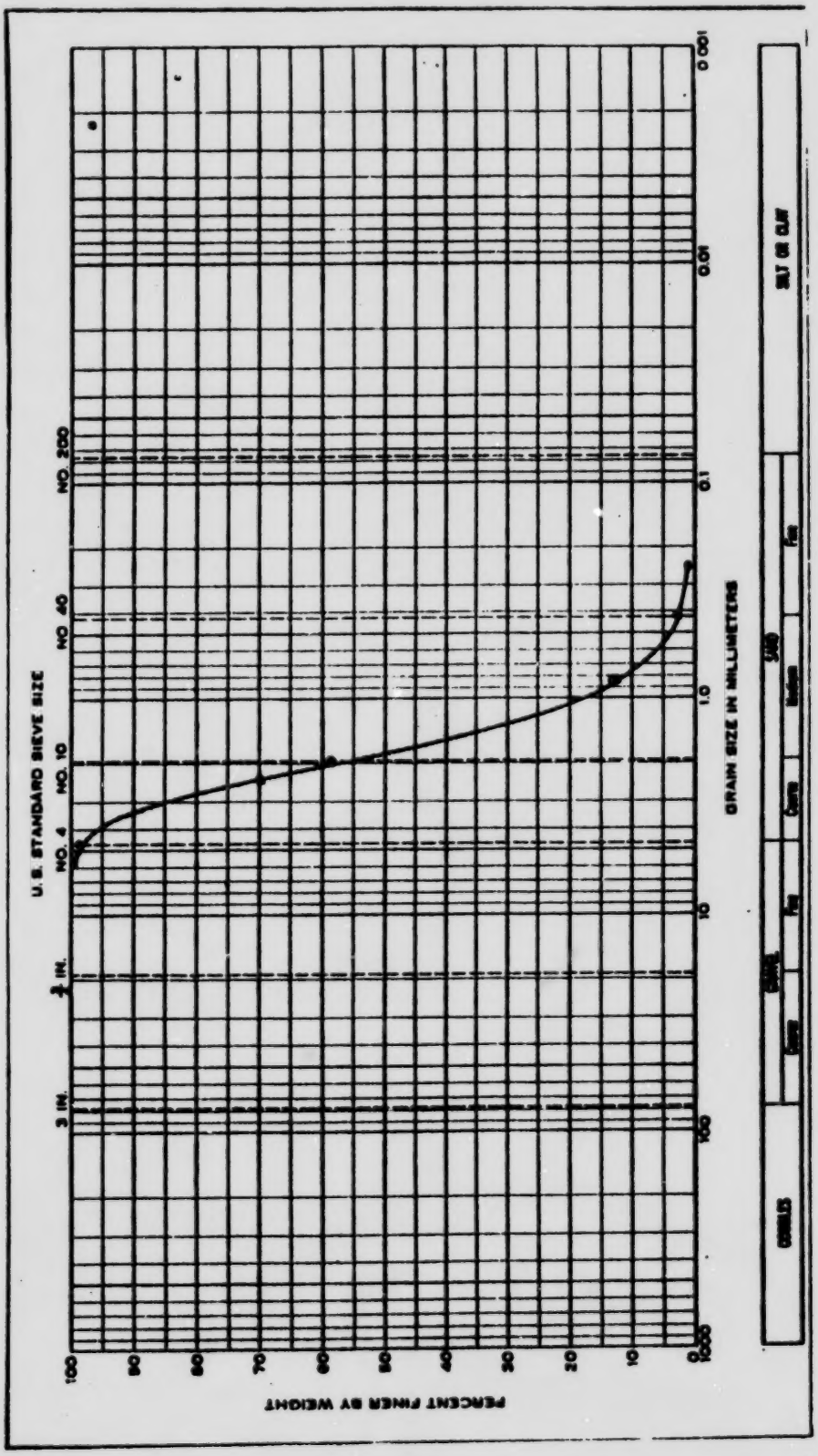

Figure 4-1. Grain Size Analysis of Rocanville Salt Tailings.

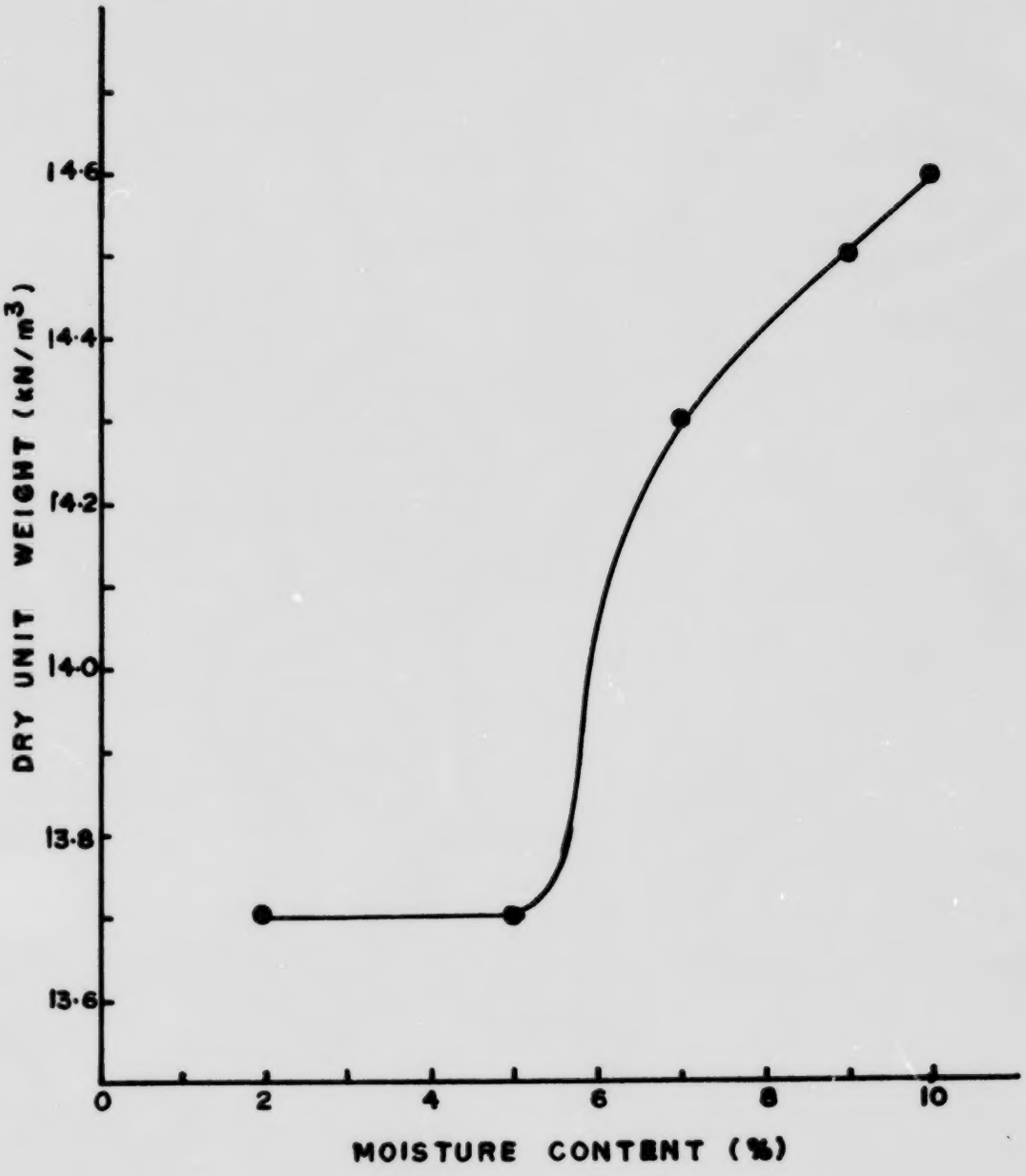

Figure 4-2. Moisture - Unit Weight Relationship for Standard Proctor Test.

marked contrast to an insoluble granular material for which a typical test would show a slightly humped curve with an optimum moisture content around 6%. Two mechanisms are probably important in causing this behaviour; angular grains become rounded and more closely packed due to dissolution at the grain contacts and aggregation of grains which commonly occur are able to break apart freeing small grains to fill some of the void spaces. High moisture contents also have some effect upon particle mobility during compaction but one would expect this effect to be optimized at lower moisture contents in common with other granular materials. A third factor is also significant; the high solubility of salt in water allows salt to be present in solution in the voids where it is not contributing to the sample volume. Comparing the samples with 2% and 10% moisture content, approximately 45% of the difference in dry density between them can be accounted for by the weight of salt in solution. (At a moisture content of 10% the salt in solution represents 3.6% of the dry weight).

4.1.4 Initial Moisture Content

The moisture content of the tailings as received was determined by drying a sample of known weight at 105°C for 24 hours. A sample taken from the centre of the tailings had a moisture content of 5.15%. Free water had drained to the bottom of the container and the water content there was in excess of 10%. Salt at the top of the container had drained to a moisture content of approximately 2%. Although we did not test specifically for rate of draining our observations were similar to those of Hesterman (1979); that is, tailings drained rapidly to a moisture content of 5 to 6 per cent and over a few days would drain to around 2%.

4.2 CONSOLIDATION TESTS

Quasi-static consolidation tests were performed at moisture contents of 2%, 5% and 10% and to maximum stresses of .034 MPa, 7 MPa and 25 MPa. Two tests were also performed to a maximum stress of 35 MPa at moisture contents

of 5% and 10%. Typical plots of stress vs. strain for quasi-static tests are contained in Figures 4-3 and 4-4. In Figure 4-3 curves for 25 MPa and 7 MPa maximum stress plot on top of one another for each moisture content; only the curves for 25 MPa are shown. The tests at a maximum stress of .034 MPa were instantaneously loaded so results for those tests are plotted as strain vs. time. Tabulated test data including initial and post-test density and moisture content are included in Table 4-1.

Samples were extruded following consolidation with the intent of performing unconfined compression tests. Only in the case of the 35 MPa tests did the samples gain sufficient cohesion during consolidation to develop any unconfined strength. Samples consolidated to 25 MPa were able to maintain their shape when extruded but could not be handled without collapsing. The moisture content of the samples was determined after consolidation in order to calculate the final wet and dry densities. When moisture loss had ocurred it was assumed that water had been lost in the form of saturated brine and that an accompanying loss of dry weight (salt) would also have ocurred. It was necessary to make this assumption because in most cases the sample had disintegrated too much during extrusion to allow accurate measurement of weight after the test.

4.2.1 Initial Density

The dry weight of all samples was 350 g when a teflon liner was used in the steel cylinder and 365 g when the liner was not used. The larger sample was used for triaxial compression tests to accommodate the size tolerance of the triaxial cell. Pilot tests demonstrated that consolidation behavior was not affected by the absence of the teflon liner.

Using a standard packing and tamping procedure the dry density of the samples with 2% and 5% moisture content was almost identical (12.80 kN/m^3 +/- 0.07 kN/m^3). At 10% moisture content the initial unit weight was approximately 8% higher (13.40 +/- .19 kN/m^3). A small amount of brine drained from the 10% moisture content samples during packing. This would clearly have a slight effect on the dry density of the sample although it would be small compared to the density difference observed.

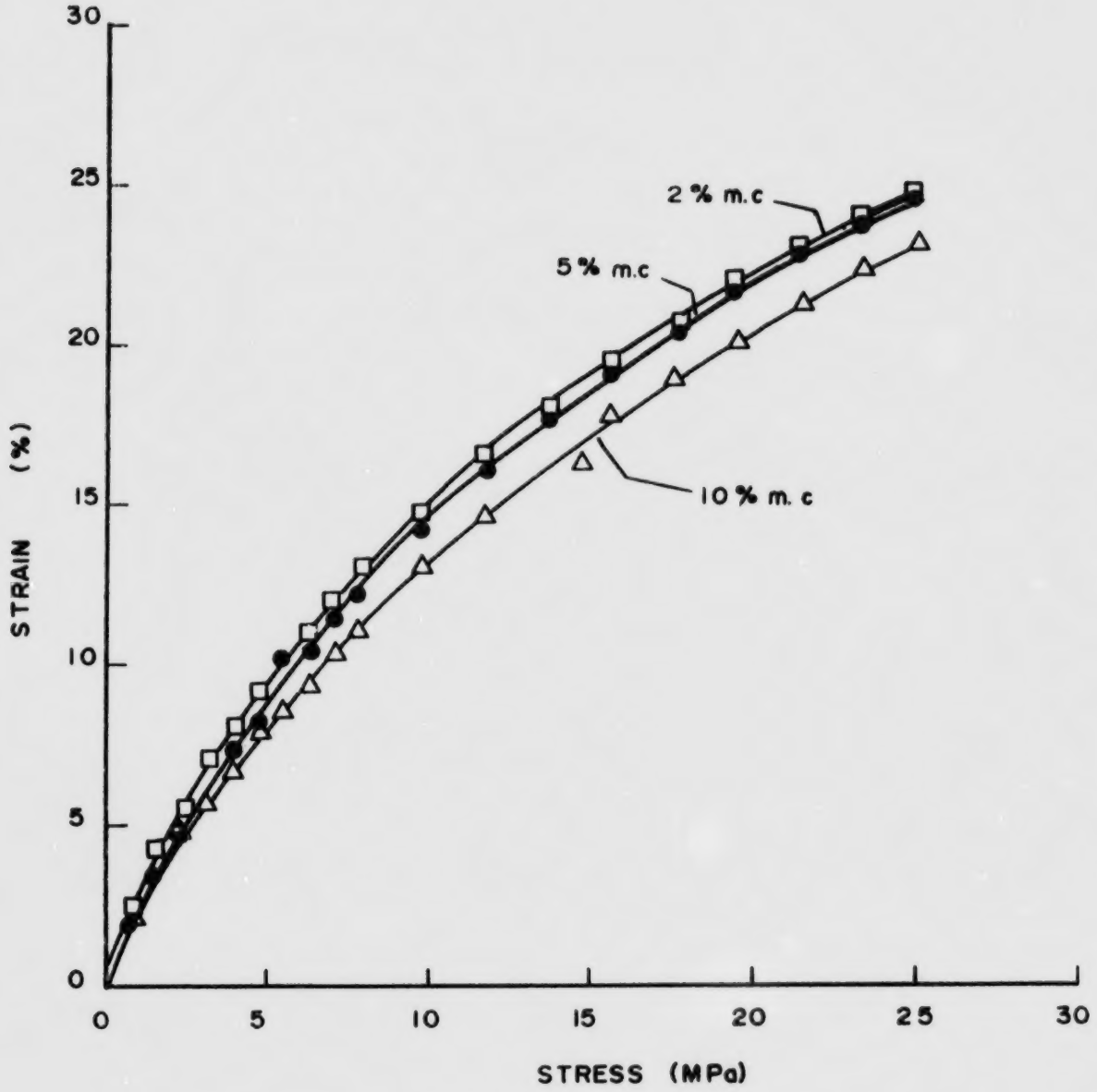

Figure 4-3. Typical Quasi-Static Consolidation Curves for Crushed Salt Tailings at Different Moisture Contents.

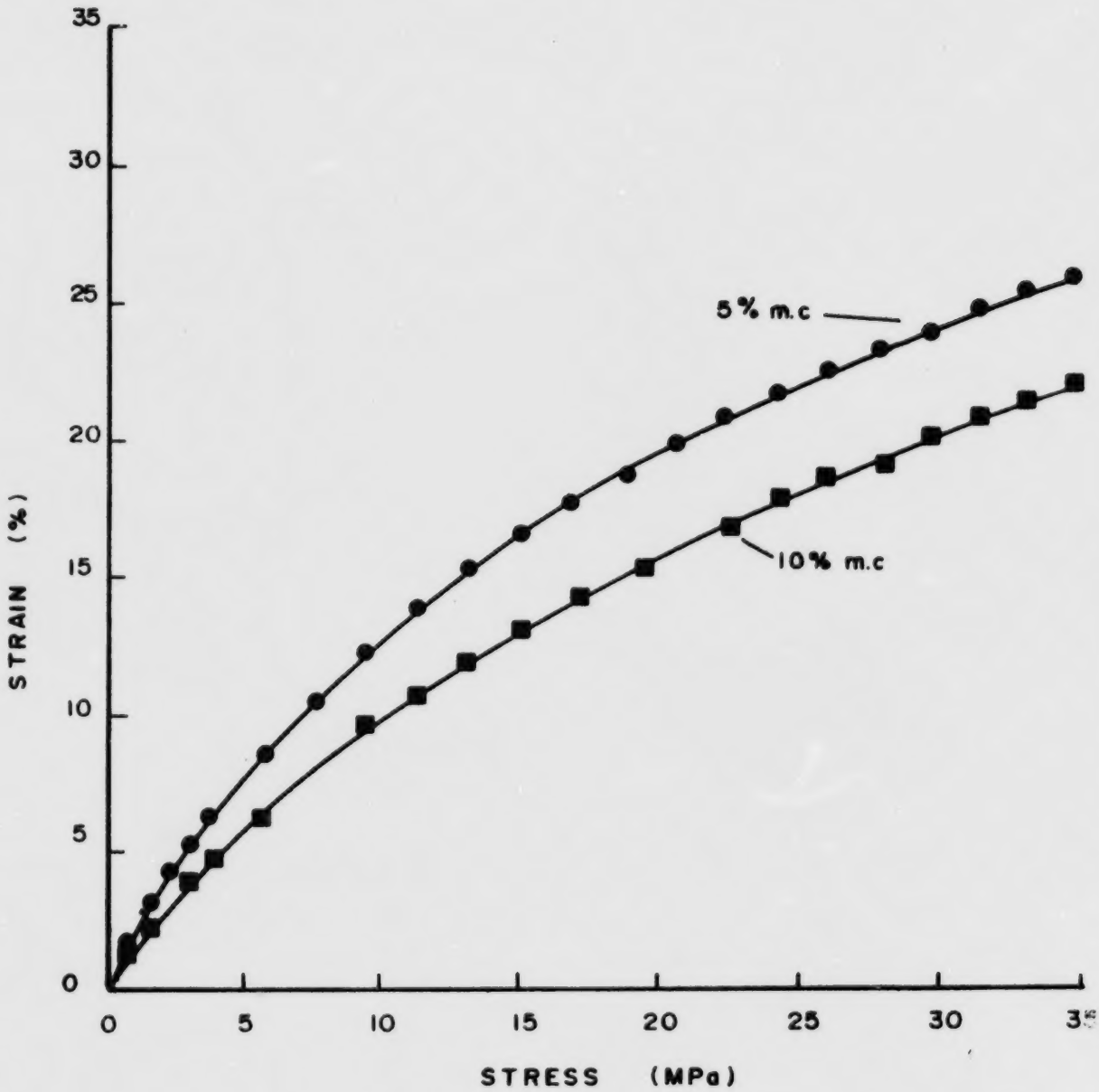

Figure 4-4. Quasi-Static Consolidation to 35 MPa Maximum Stress for Moisture Contents of 5% and 10%.

Table 4-1. Results of Quasi-Static Consolidation Tests

Sample No.	Moisture Content (%)		Dry Unit Weight (kN/m^3)		Maximum Stress (MPa)
	Original	Final	Original	Final	
1	0.8	0.8	12.68	16.93	25
2	2.0	2.0	12.83	17.01	25
3	2.0	2.0	12.83	17.04	25
4	2.0	2.0	12.83	14.53	7
5	2.0	2.0	12.74	14.30	7
6	5.0	5.0	12.74	14.27	7
7	5.0	5.0	12.74	16.96	25
8	5.0	5.0	12.93	17.14	25
9	5.0	5.0	12.74	14.49	7
10	10.0	6.0	13.74	15.27	7
11	10.0	6.0	13.02	14.47	7
12	10.0	3.7	13.42	17.13	25
13	10.0	3.5	13.42	17.16	25
14*	5.0	5.0	12.42	16.44	25
16	10.0	3.6	13.39	16.87	35
17	5.0	2.4	12.65	16.98	35
T01	5.0	5.0	12.99	16.90	25
T02	5.0	5.0	12.61	16.38	25
T03	5.0	3.4	12.79	16.56	25
T04	5.0	5.0	12.51	16.22	25
T05	5.0	3.0	12.70	16.21	25
T06	5.0	5.0	12.61	16.30	25
T07	5.0	5.0	12.51	16.22	25
T08	5.0	5.0	12.79	14.16	7
T09	5.0	5.0	12.79	15.24	14
T10	5.0	5.0	12.42	14.82	14
T11	5.0	5.0	12.61	15.00	14
C01	5.0	5.0	12.70	16.47	25
C02	5.0	5.0	12.61	16.36	25
C03	5.0	5.0	12.61	16.01	25

* Sample was unloaded and reloaded at two intermediate stresses prior to reaching maximum consolidation stress.

4.2.2 Loading Conditions

The load was applied using a constant deformation rate of 1.5 mm per minute. A comparison was made with a sample loaded at 5 mm per minute and the consolidation was found to be almost identical. Slower rates would presumably introduce a significant creep component to the consolidation response although this aspect was not studied specifically. At 25 MPa specimens originally creeped at rates of 0.5 to 0.2 mm per minute indicating that load rates as low as this would cause significant creep during consolidation. The load-deformation relationship was very reproducible for samples with the same initial moisture content. At 7 MPa the greatest difference between the percentage consolidation of samples with the same moisture content was 9% and at 25 MPa it was 10%.

4.2.3 Effect of Moisture Content on Consolidation Behavior

Variation of moisture content in the range 0 to 5% had minimal effect upon the initial or final dry unit weight of consolidating samples. The load-consolidation curves also showed good reproducibility with variations in moisture content within this range. The difference in dry density between the samples at 5% moisture content or less and those with 10% moisture content decreased with increasing load. (See Figure 4-5). At 7 MPa the latter were only 3% higher. Thus, it appears that the dry unit weight after consolidating under high loads is not dependent upon the initial moisture content. Although water seems to have a lubricating effect at low stresses, allowing closer packing, it is either not important at high stresses or only very small quantities of water are required to provide the maximum lubrication effect. These results imply that the mechanisms involved in quasi-static consolidation do not change with moisture content; that is any pressure dissolution, fusion of crystals or recrystalization that takes place does so independently of moisture content within the limits tested.

The relationship between dry unit weight and moisture content at the various stress levels is shown in Figure 4-5. The decreasing influence of moisture content as stress increases can be clearly seen. Figure 4-6

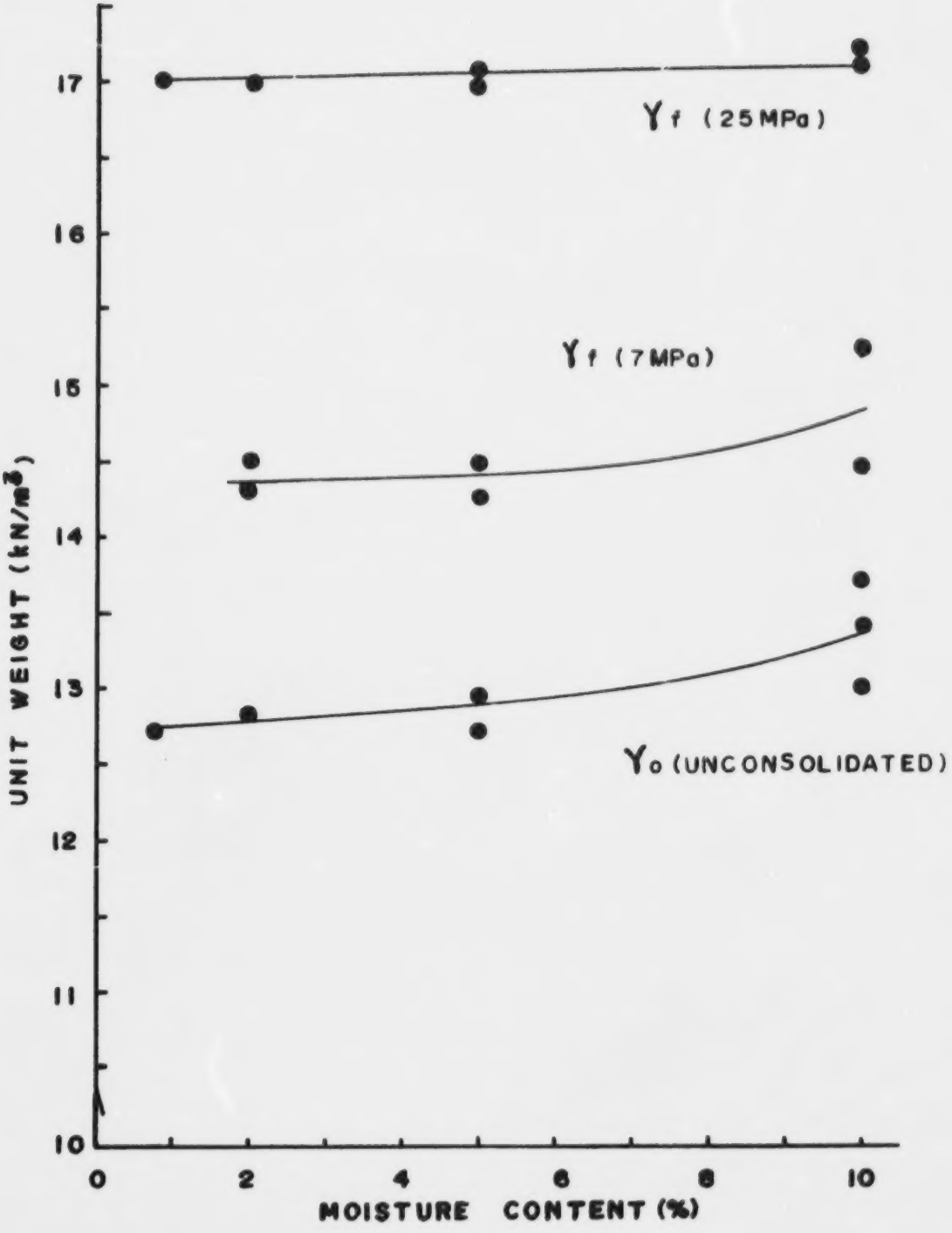

Figure 4-5. Relationship Between Unit Weight and Moisture Content at Various Stress Levels.

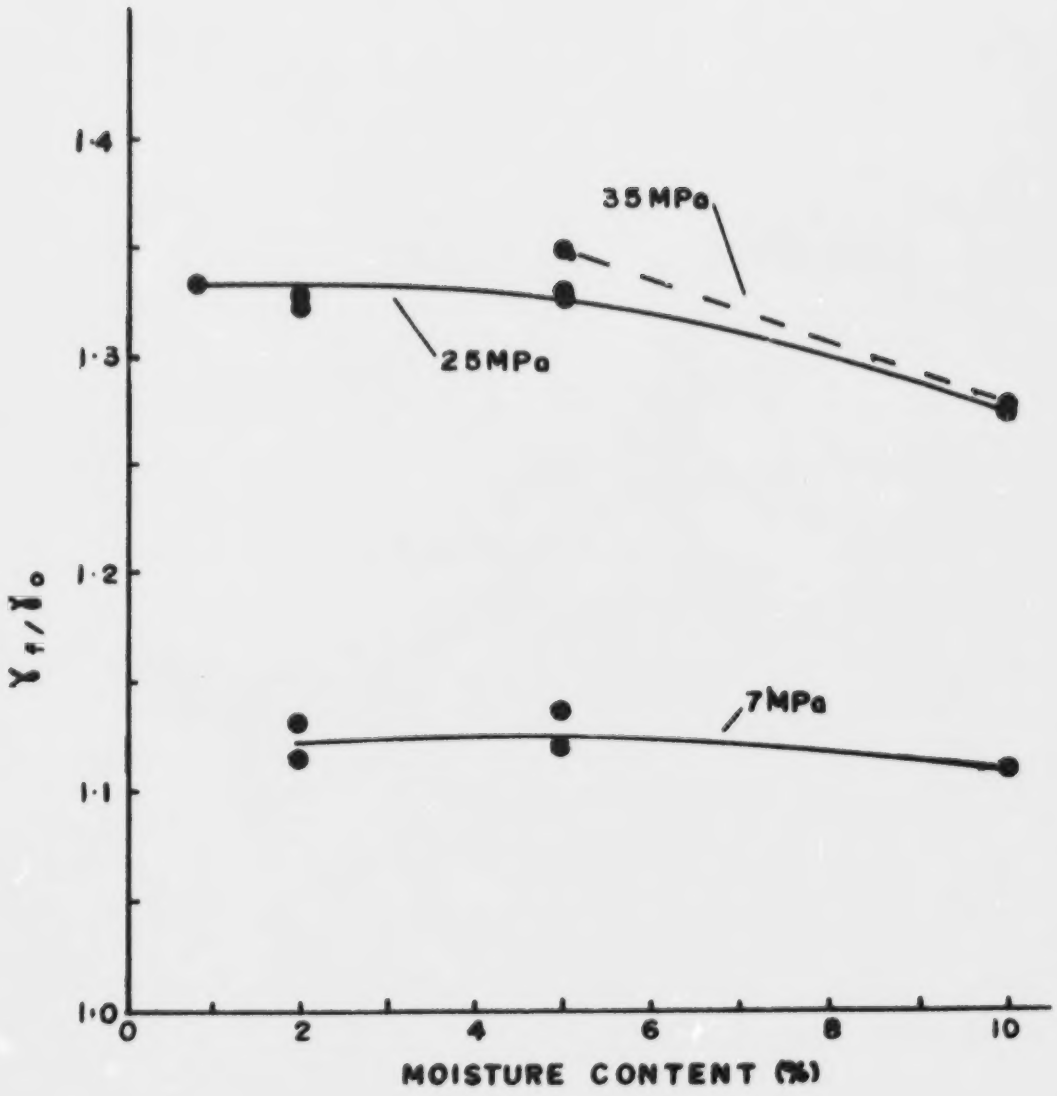

Figure 4-6. Relationship Between Moisture Content and Change in Unit Weight During Consolidation to Various Levels of Maximum Stress.

illustrates the relationship between the ratio of final to initial dry unit weight and moisture content. As a result of the higher initial unit weight which is obtained with a high moisture content, the change in volume, and hence unit weight, which occurs during consolidation is reduced. Thus it appears that optimum performance from the fill can be obtained by packing it at a moisture content which will give the highest density for a given compactive effort. A test such as the standard or modified Proctor test can be performed to determine the moisture content at which this optimum density is achieved. The results of a standard Proctor test are discussed in Section 4.1.3.

4.2.4 Low Stress Consolidation Tests

A series of tests was performed under dead load at a stress of 0.034 MPa (5 psi). Although these are included in the consolidation testing portion of the work they were necessarily run as creep tests over a period of one week as this small load could not be quasi-statically applied. The results for moisture contents of 2%, 5% and 10% are shown on Figure 4-7. Again, all samples were packed into the steel tubes using the standard procedure and as a result the initial density of the sample with a moisture content of 10% was 5% higher than the other two samples. The three samples strained at almost identical rates despite the wetter sample being initially more dense. This indicates that at low stress free water has a marked effect in facilitating consolidation and closer packing of the salt grains. Quasi-static tests showed that the unit weight at 25 MPa was independent of moisture content, suggesting a change in behavior either at higher loads or under creep versus quasi-static loading conditions. After one week under load the sample with 10% initial moisture content had a moisture content of 4.8%; it is estimated that the moisture content decreased to around 7% in 1 hour and to 5% after 2 to 3 days. No unconfined strength was developed by samples in this series of tests indicating that little grain bonding had taken place.

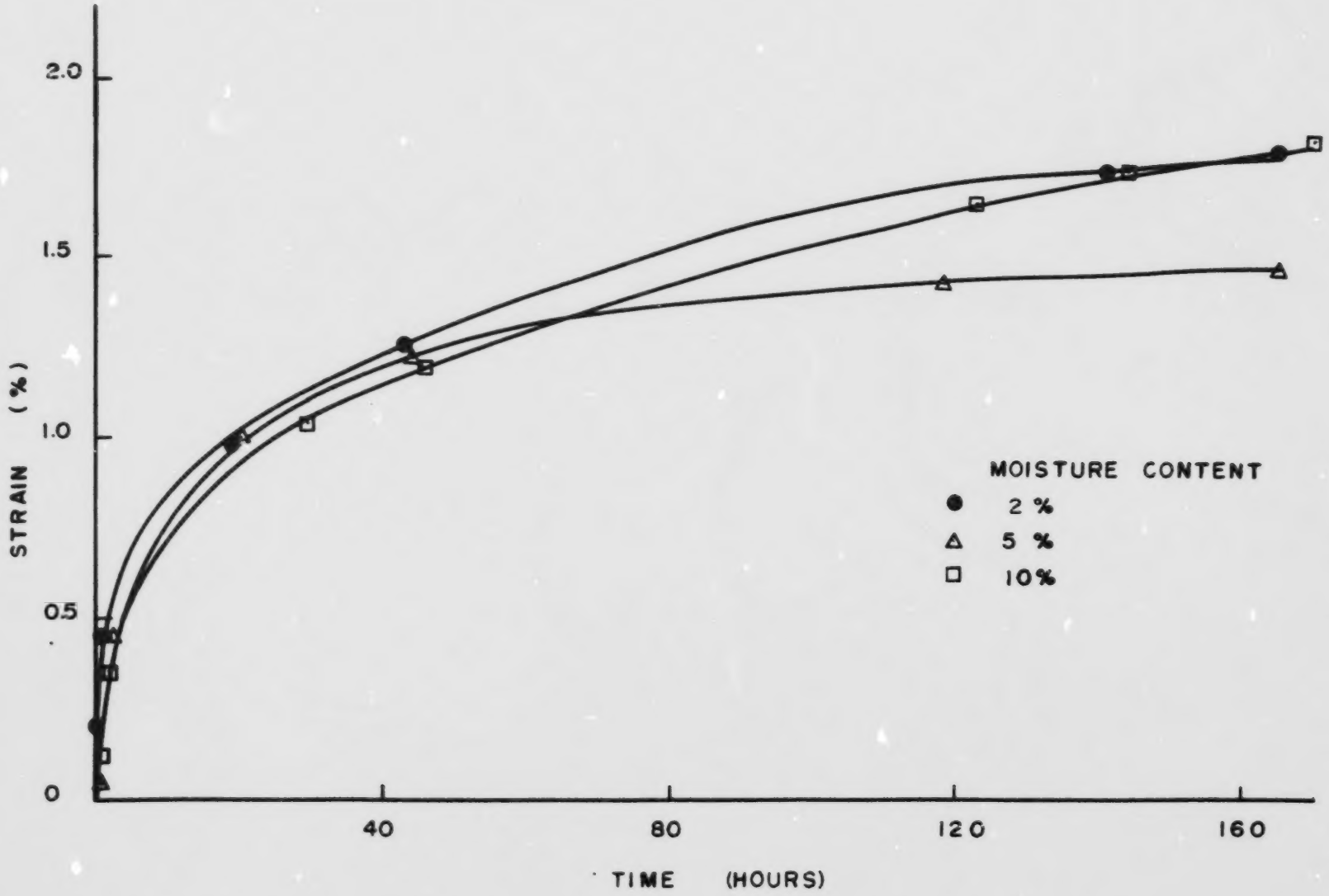

Figure 4-7. Creep Consolidation of Salt Tailings Under a Stress of 0.034 MPa.

4.3 CREEP TESTING

Following quasi-static consolidation to the maximum applied load additional consolidation takes place under constant stress conditions. A preliminary study of the rate of this creep consolidation, its dependence upon moisture content and the effect of increase in density upon strength was undertaken. This study had two components. First, a number of the quasi-static tests were maintained at maximum load for approximately 10 minutes to study the initial rate of creep. This allowed the effect of moisture content to be studied at different stress levels by an approximate but relatively rapid method. Figures 4-8 and 4-9 indicate that consolidation during the creep phase has a low dependency upon moisture content within the range tested, both at 7 MPa and 25 MPa stress. Second, three samples were left under a stress of 25 MPa +/- 0.5 MPa for periods of 7, 14 and 25 days. These samples all had moisture contents of 5% and were used to study the relationship between time under load and strength. Only unconfined strength tests could be performed due to the limited number of samples prepared under creep conditions.

Figure 4-10 illustrates the time dependent consolidation/creep of these specimens. The corresponding quasi-static consolidation curves for these samples are contained in Appendix A. It will be noted that the three curves are all very similar in form. This indicates that the testing method provides consistent and reproducible results. The curves, as expected, are asymptotic to some value of strain. Since consolidation of the salt is taking place within a rigid steel tube, closure will stop once all void spaces have been filled and any free water dispelled. Samples C 02 and C 03 have reached a unit weight of 18.8 kN/m^3; their void content is approximately 12%. The moisture contents have been reduced to 1.2% and 1.3% respectively. Maximum consolidation is approximately 32%, of which about 10% occurred during creep.

Sample C 03 underwent slightly less strain during quasi-static consolidation than the other two samples and thus remains at a

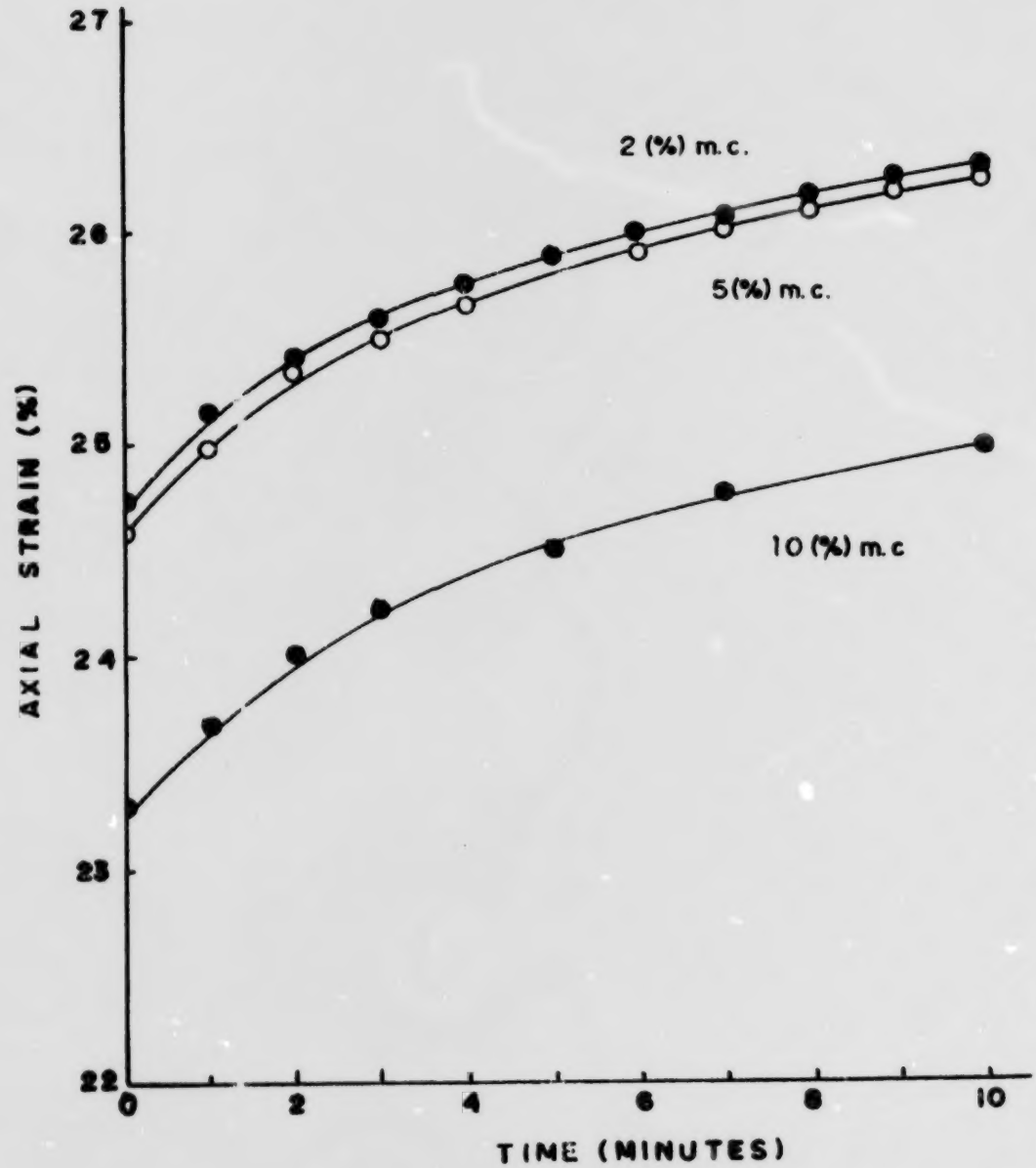

Figure 4-8. Short Term Creep of Salt Tailings Under 7 MPa Axial Stress.

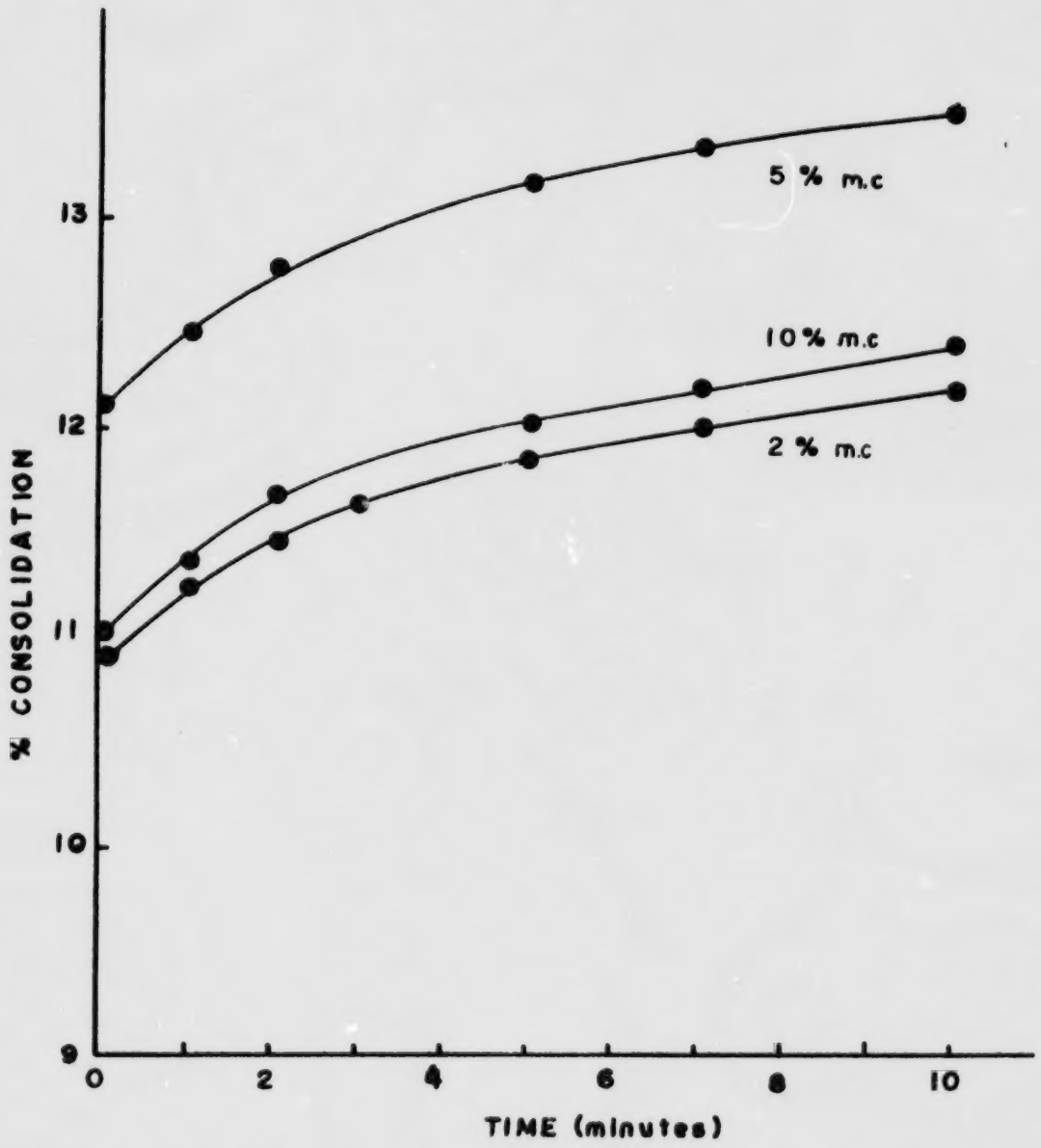

Figure 4-9. Short Term Creep Consolidation of Salt Tailings Under 25 MPa Axial Stress.

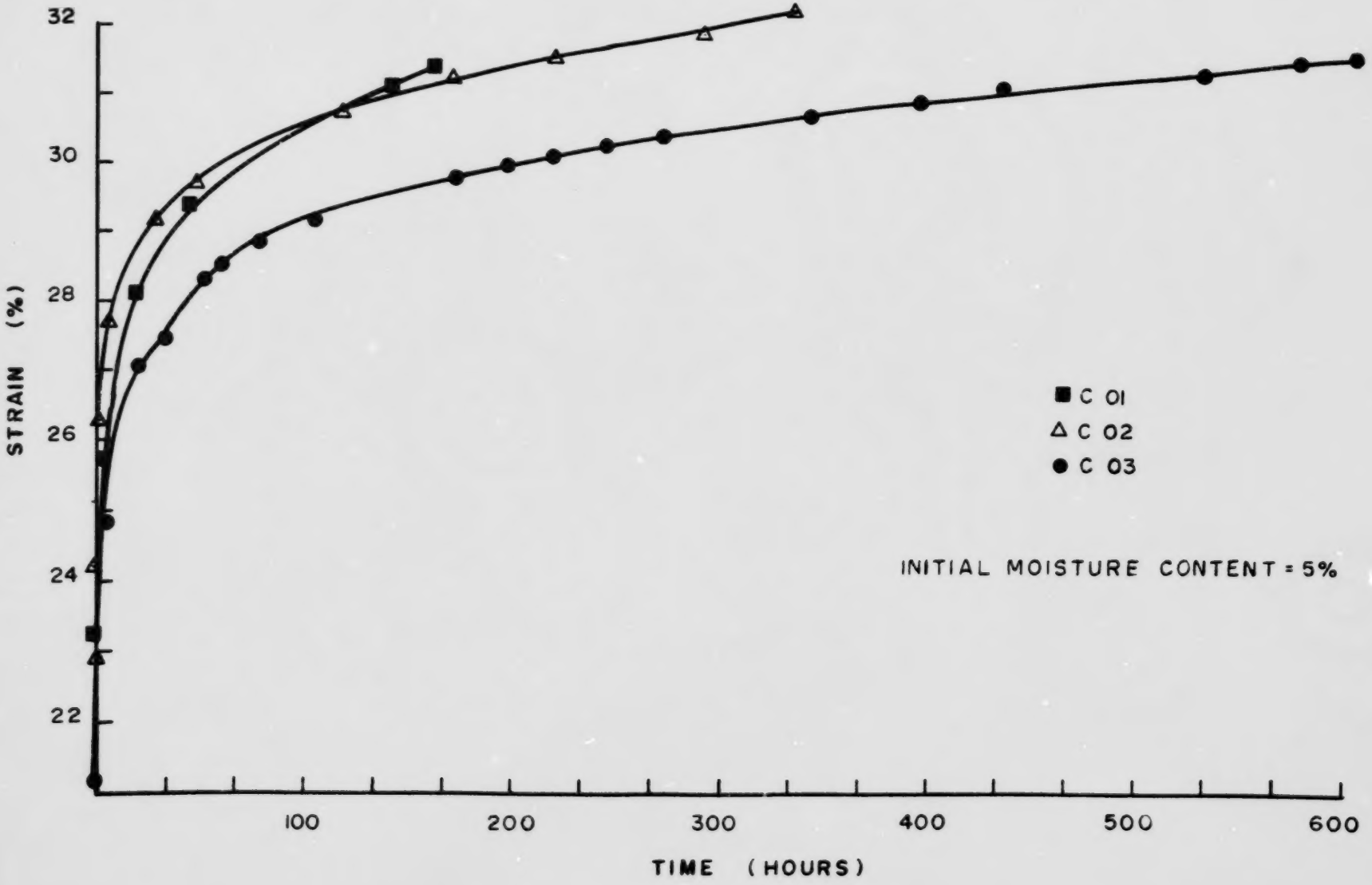

Figure 4-10. Creep Consolidation Curves for Salt Tailings at 25 MPa Axial Stress.

consistently lower strain level during the creep test. Its final dry density is similar to that of C 02 because of the greater time under load.

The creep tests demonstrated that a coherent material could be formed in a relatively short period of time and that time under load is probably a more important consideration than maximum load in determining the strength of the consolidated tailings. This aspect is discussd in greater detail in Section 5 of this report.

In addition to performing strength tests on the consolidated samples, fractured samples were viewed with light and scanning electron microscopes to provide information about the nature of the intergranular bonds which have formed while under load. The results of the study are also discussed in the following section.

4.4 POST-TEST CHARACTERIZATION OF CONSOLIDATED SAMPLES

4.4.1 Quasi-Static Consolidation Tests

The intent of the project was to perform uniaxial and/or triaxial commpression tests on all samples prepared by quasi-static consolidation. In practice, many of the samples collapsed under self-weight when extruded from the steel tubes, and others were unable to sustain any applied load. The only sample with a measurable strength was that consolidated to 35 MPa at 10% moisture content; its strength was 1.28 MPa. Of samples consolidated to 25 MPa, the samples with 5% moisture content were the most coherent but they did not possess a measurable strength ('measurable' is defined as greater than 0.2 MPa for the load frame used). As a consequence of this problem it was decided to allow all samples used for strength testing to remain under the maximum load for a period of 10 minutes following quasi-static consolidation in order to gain sufficient strength to allow handling. All samples prepared specifically for strength testing had a moisture content of 5%.

4.4.2 Triaxial and Uniaxial Compressive Strength

The unconfined strength of a crushed salt sample prepared in the manner described above, and with a maximum stress of 25 MPa, was 2.9 MPa. With a maximum stress of 14 MPa it was 0.20 MPa and at 7 MPa the sample had no unconfined strength. The preparation of samples by quasi-static consolidation to a stress of 7 MPa was abandoned in favour of a maximum stress of 14 MPa because those prepared at the lower stress could not withstand the handling necessary for triaxial testing. Under uniaxial stress, the load at failure was well defined and failure progressed rapidly. A shear plane was generally not clearly apparent.

For samples prepared at a maximum stress of 25 MPa, triaxial tests were performed at confining pressures of 2.5, 5, 10, 12 and 20 MPa. Typical stress-strain curves for these tests are shown in Figure 4-11. It will be noted that all tests display similar behavior. Following an initial seating of the specimen a period of elastic behavior occurs. Yielding is followed by another section in which the stress-strain relationship is almost linear but in which all deformation is irrecoverable. Some samples which were loaded to very high strains show a gradual transition from linear behaviour to complete failure but most had buckled before this point so that load could no longer be applied safely. We postulate that this yielding behaviour represents general rather than localized failure taking place at yield and that the material is sufficiently contained by the membrane of the triaxial cell to enable it to behave as a frictionless material while still supporting load. For the purpose of constructing a Mohr's envelope it was necessary to establish a failure criterion. Failure was arbitrarily defined as the stress at 5.0% strain. This corresponds to the upper end of the yield portion of the stress-strain curve and is approximately the point at which a weak sedimentary rock such as shale or claystone would fail.

For samples consolidated to 14 MPa maximum stress triaxial tests were performed at confining stresses of 2.5 MPa and 5 MPa. The stress-strain relationships are similar to those described above and the failure stress was established in the same way.

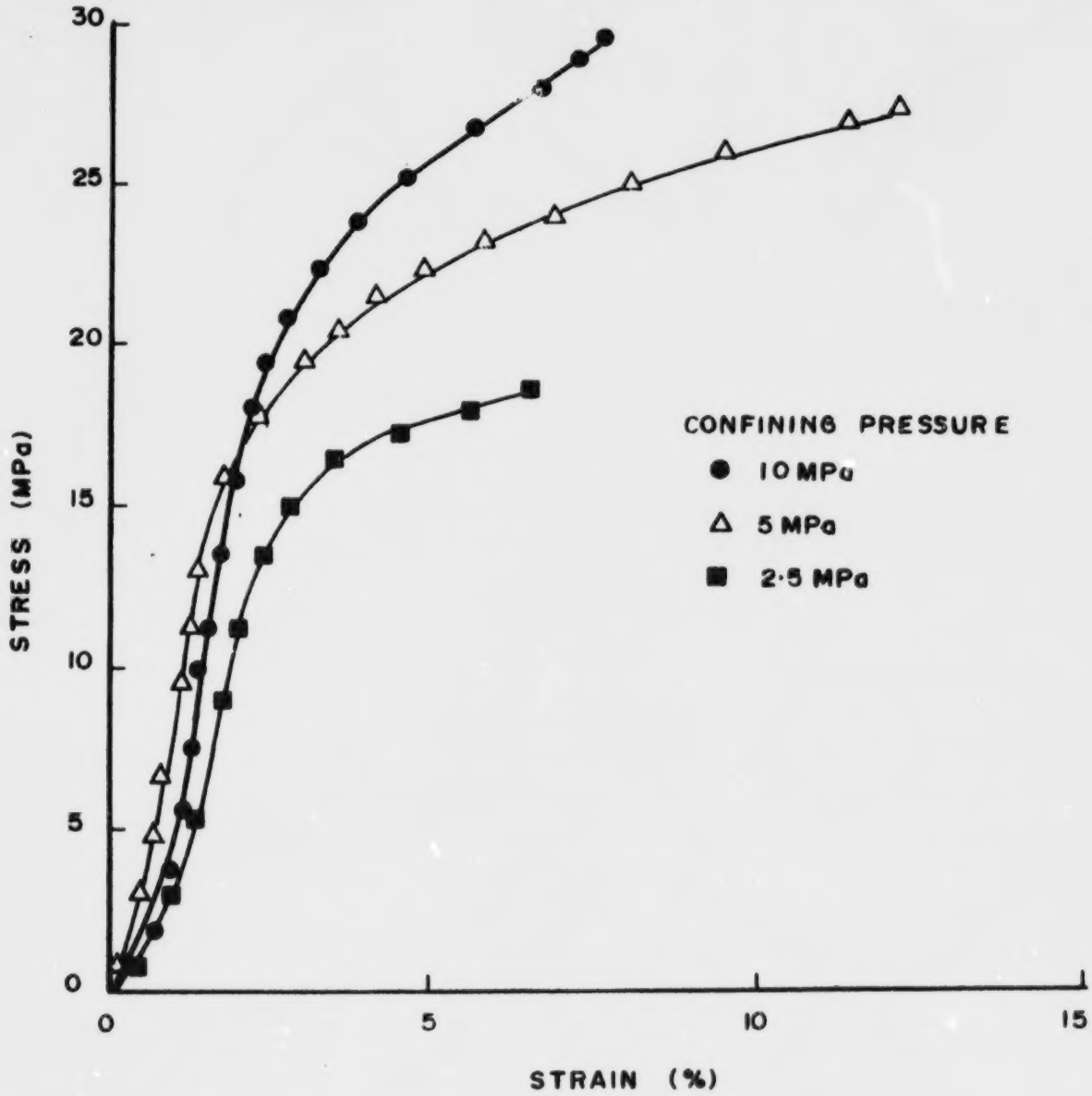

Figure 4-11. Typical Stress-Strain Curves for Salt Tailings Consolidated to 25 MPa and Tested Under Triaxial Compression.

Mohr's envelopes for the two triaxial series are shown in Figures 4-12 and 4-13. Both indicate increasing shear strength with increased confinement up to a confining pressure of about 5 MPa. Above 5 MPa there is no longer any dependency of strength on confining pressure. This indicates that at higher confining pressures failure does not occur along shear planes but is a more general collapse or slumping which depends only upon deviatoric stress. If the slope of the envelope at very low confining pressures were considered, an angle of friction of 45° to 50° and a cohesion intercept of 0.2 to 0.5 MPa would be indicated. Clearly however, the shape of the envelope is such that a straight line fit is inadequate for most purposes.

Strength data and elastic moduli for these compressive strength tests are compiled in Table 4-2. The confined tangent modulus before yield is 1.18 +/- .46 GPa and compares with a typical value of 30 GPa for solid rock salt.

4.4.3 Moisture Content and Unit Weight

Following each quasi-static consolidation test the moisture content and unit weight of the consolidated sample was determined. Unit weights were calculated from the initial height of each specimen and the measured consolidation. Direct measurements of the extruded, consolidated sample were not usually possible. Moisture contents were determined by drying a sample of 50 to 100 g at 105°C for 24 hours. There was no loss of moisture during consolidation to 25 MPa for samples with 2% and 5% initial moisture content. At 5% initial moisture content water loss began almost immediately during the creep phase at a stress of 25 MPa and began between 25 MPa and 35 MPa for samples loaded to higher stresses. Samples with 10% initial moisture content lost water throughout consolidation and had a final moisture content of 6.0% at 7 MPa and 3.5% at 25 MPa.

The increase of unit weight during consolidation has been discussed previously in Section 4.2. All unit weights and moisture contents are tabulated with other data in Table 4-1.

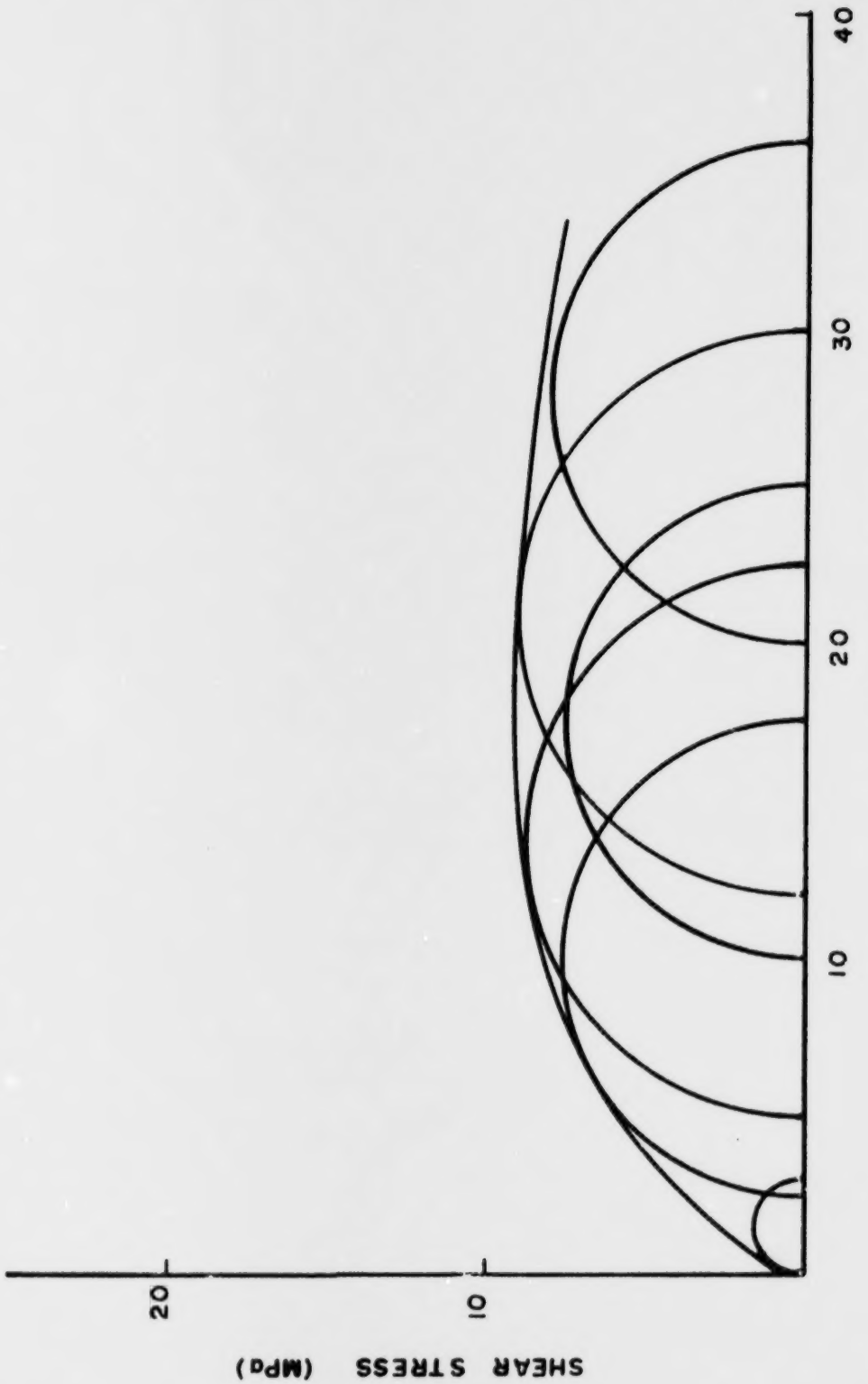

Figure 4-12. Mohr's Circles for Salt Tailings Consolidated to 25 MPa.

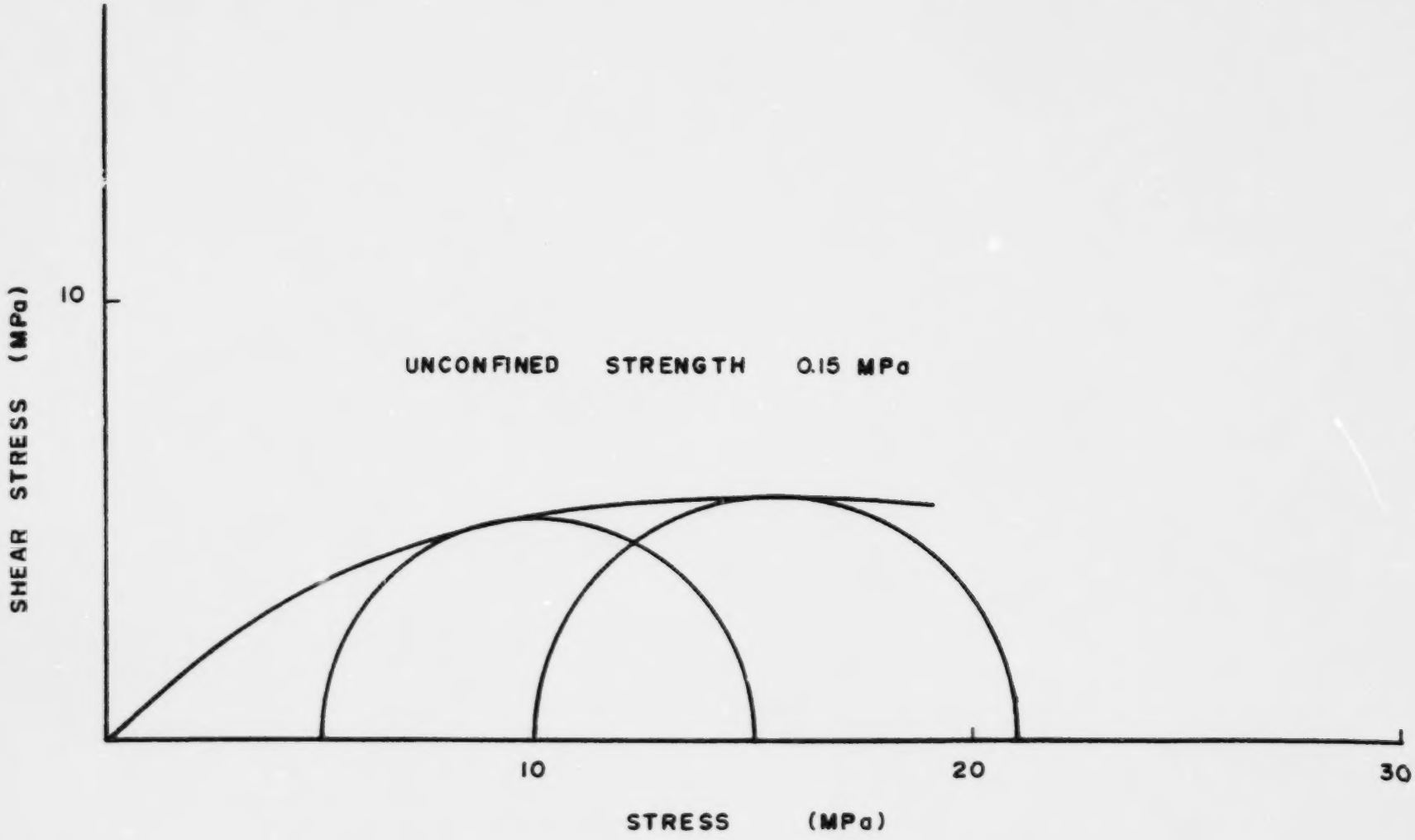

Figure 4-13. Mohr's Circles for Salt Tailings Consolidated to 14 MPa.

Table 4-2. Material Properties for Samples Tested Under Triaxial Compression

Sample No.	Maximum Consolidation Stress (MPa)	Unit Weight (kN/m^3)	Confining Pressure (MPa)	Young's Modulus (MPa)	Ultimate Stress at Yield (MPa)
T02	25	16.84	10.0	1282	25
T03	25	16.93	2.5	952	16
T04	25	16.49	5.0	1163	22
T05	25	16.58	0	340	3.0
T06	25	16.59	20.0	1375	36
T07	25	16.48	12.0	2049	30
T09	14	15.49	0	-	0.15
T10	14	15.07	5.0	436	15.0
T11	14	15.21	10.0	380	21.0

NOTE: - all samples consolidated at 5% moisture content
- yield defined as 5% axial strain

4.4.4 Creep Tests

Following various periods of time under static load of 25 MPa creep samples were extruded from their steel tubes for unconfined compression testing. At the same time, unit weight and moisture content were determined. Two samples were also studied with an electron microscope (Cambridge Stereoscan 150) in order to provide some insight into the mechanisms responsible for strength gain.

While samples consolidated under quasi-static conditions could be extruded from the steel sleeve using relatively low pressures (around 1.5 MPa) those from the creep tests required pressures of 10 to 15 MPa. In the case of the sample under load for 25 days, the high extrusion pressure caused a lateral fracture approximately 10 mm from the ram face and the sample ejected rather violently. This was presumably caused in part by elastic energy stored in the steel tube.

4.4.4.1 Strength Tests

Unconfined compression tests were performed on samples consolidated under 25 MPa for each of 7, 14 and 25 days. Stress-strain curves for each of these tests are shown in Figure 4-14. The 25 day sample required capping in order to test it because of the fracture that occurred during extrusion. This undoubtedly had some effect upon its strength. The unconfined strength of the three samples was 10.4, 14.0 and 11.6 MPa respectively. All broke in a ductile manner; the last sample failed by bulging while the two earlier samples developed distinct shear planes. The Young's Modulus for all samples was 833 MPa. It is interesting to note that these moduli values are very similar to those found in triaxial testing of much less consolidated specimens, despite the creep specimens having much higher unconfined strengths. Test results are tabulated in Table 4-3.

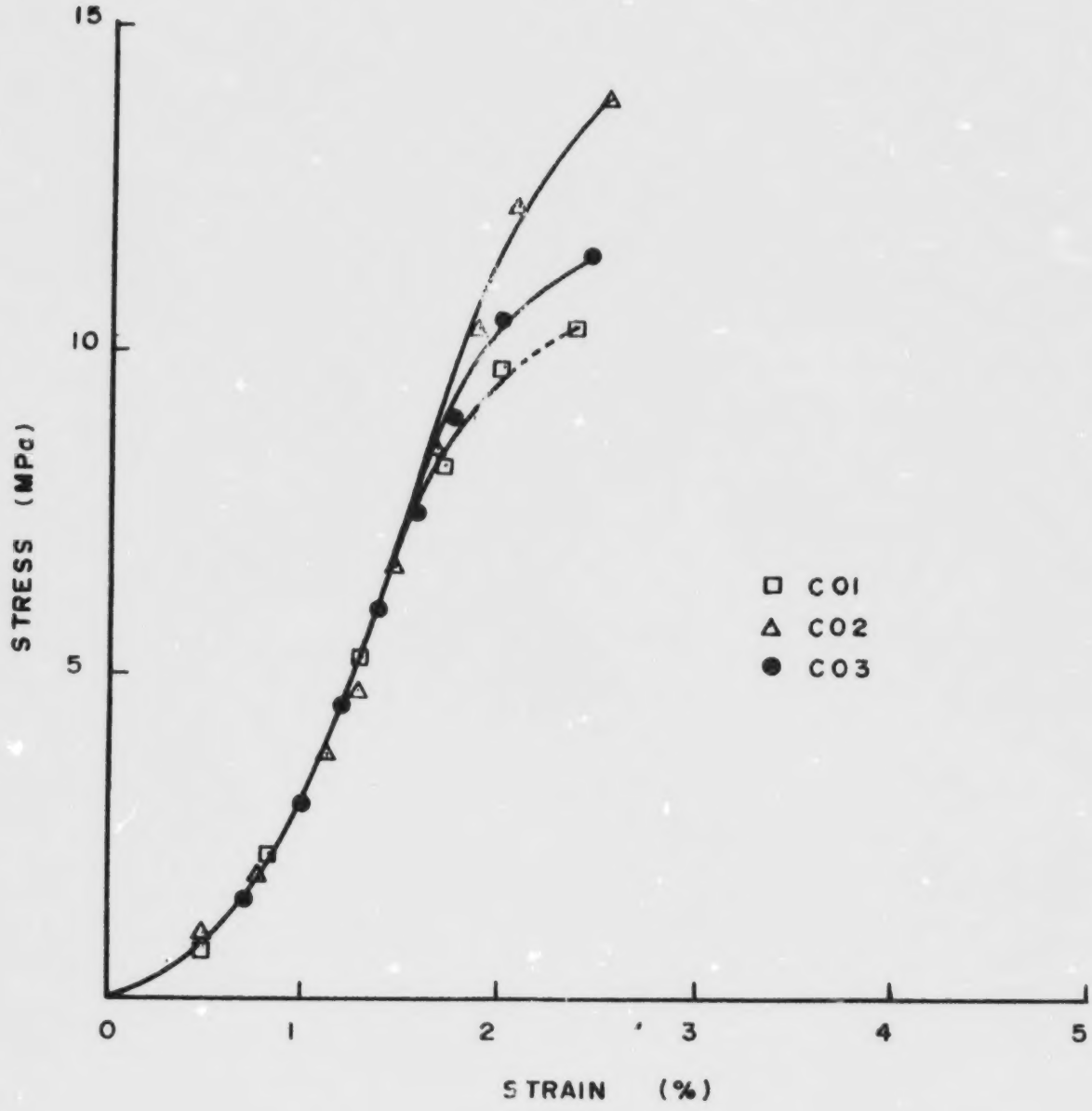

Figure 4-14. Stress-Strain Curves for Uniaxial Compression Tests on Salt Tailings Consolidated at 24 MPa Under Creep Conditions.

4.4.4.2 Density and Moisture Content

The moisture content of the tailings decreased from 5% initially to 2.3% after 7 days and to 1.3% after 25 days. The unit weight had increased to 18.7 kN/m^3 or 89% of the density of solid salt at 25 days. Complete results are tabulated in Table 4-3.

Table 4-3. Post-Test Data for Creep Tests

Sample No.	Time Under Load (days)	Weight (kN/m^3)	Final Moisture Content (%)	Young's Modulus (MPa)	Unconfined Strength (MPa)
C01	7	18.2	2.1	833	10.4
C02	14	18.8	1.2	833	14.0
C03	25	18.7	1.3	833	11.6

Note that although the samples still have 10% porosity at the end of the test, considerable liquid has been squeezed from the pores. Loss by evaporation is assumed to be negligible because of the close fitting plattens at either end of the sample.

4.4.5 Microscopy

The mechanisms which are responsible for increasing the unconfined strength of salt tailings during consolidation and creep were not clear from the strength testing program alone. In order to better understand progressive strength development it was decided to initiate a small study using an electron microscope.

It was clear from the testing program that simply consolidating the tailings rapidly under quasi-static conditions produced very little strength and that minimal intergranular bonding could have taken place. However, a considerably greater strength is developed by tailings which are simply allowed to sit for an extended period and consolidate under their own weight. Randomly packed grains are shown in Plate 4-1(a) where it is seen that almost all grain contacts have a small pad of recrystallized salt interconnecting the adjacent grains. Plate 4-1(b) shows a typical grain connection. These "bridges" are presumably caused by partial evaporation of the pore water and consequent recrystallization.

Plates 4-1(c) and 4-1(d) show typical grain boundaries in a salt sample which has been under a load of 25 MPa for 25 days. The fine "bridge" structures are no longer present and grain contacts are considerably more intimate. Preferential dissolution and recrystallization has taken place so that edge to corner contacts can seldom be found. The large numbers of small grains seen in the previous sample are no longer present; they appear to have become fused into agglomerations in which the original grain boundaries are unclear.

Finally, a group of salt crystals within the solid potash bearing rock were studied. Here, crystal faces are uneven and few clear cubic cleavages are evident. Minimal void space can be seen; Plates 4-1(e) and 4-1(f). This sample may be seen as the final stage of the consolidation process which was observed in the previous plates.

Plate 4-1. Scanning Electron Micrographs of Salt Tailings.

(a) General view of unconsolidated, dry salt tailings.

(b) Grain contact in unconsolidated tailings.

(c) Grain contact following creep consolidation.

(d) Detail of reprecipitation at grain contact in (c).

(e) General view of rock salt crystal.

(f) General view of rock salt crystal.

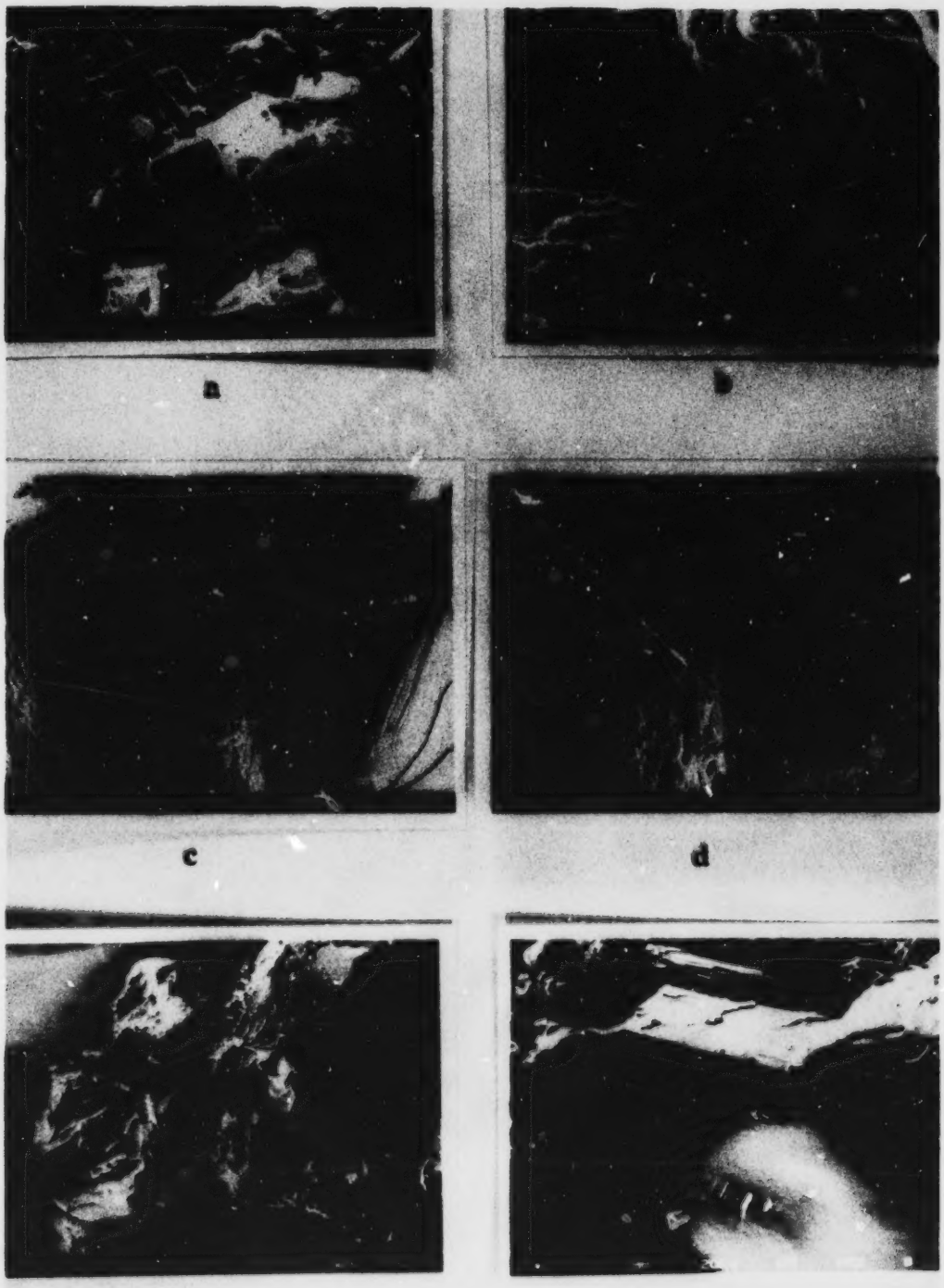

Plate 4-1

5 DISCUSSION

This study has focused upon three specific areas of salt tailings behavior. Most importantly, the effect of moisture content upon consolidation behavior has been studied. Second, the strength and elastic properties of the tailings have been studied immediately following quasi-static consolidation. Lastly, the response of consolidated tailings to a constant high load (creep) has been examined. Ancillary studies were made to support the hypotheses resulting from these tests and to explain any unexpected behavior.

5.1 CONSOLIDATION TESTS

Quasi-static consolidation tests demonstrate that as the loads increase the importance of initial moisture content decreases. Although the moisture content has a significant influence upon the initial density of the tailings packed into the tube, its influence on density at 25 MPa was negligible. A standard Proctor test confirmed that between 5% and 10%, increasing moisture content has a significant impact upon the density achieved during packing. As a result of a higher initial density, tailings with 10% moisture content exhibit a smaller change in volume during consolidation than material with lower moisture content. Clearly this is an advantage for a mine backfill where rapid uptake of load and the ability to minimize subsidence are important. Although this conclusion conflicts with that of Miller (1983) it appears that the latter failed to correct for variations in the initial density of tailing samples and that this appears to have introduced considerable errors.

The standard Proctor test provides an interesting insight into the behavior of salt tailings. Minimal increase in dry density between 2% and 5% moisture content suggests that the lubricating action of the water is not the major cause of increasing density as it would be with a fine gravel. Preferential dissolution at contact points during the compaction process is one probable cause of increased density with higher moisture contents.

This would presumably have to take place with simultaneous re-precipitation as the brine is saturated before the test. The third possible cause is that the many small grains which adhere to larger ones can be removed during compaction at high but not at low moisture contents. A brief microscopic study of salt grains revealed that in the dry state small grains adhered to larger ones strongly enough to withstand manipulation on the microscope stage but that when wet they could readily be dislodged by the same effort. This reinforces the argument for placing tailings with a high moisture content. Facilities for handling the brine draining from the tailings must be able to cope with 140 to 150 litres of saturated brine per cubic meter of tailings placed at 10% moisture content. Approximately 50% of this volume is likely to drain within the first few hours. The possible requirement for dilution of the saturated brine to avoid recrystallization of salt in the pumps and lines must be considered.

Minimal strength is imparted to the tailings by quasi-static consolidation, even at very high loads. This indicates that mechanical interlock is not responsible for significant strength but that grain bonding, which is a function of both time and stress, is required for strength development. Since strength develops very quickly if high loads are maintained the relationship between the three variables, strength, time and stress could presumbaly be established relatively easily.

Consolidation tests at a stress of 0.034 MPa (5psi) were intended to simulate behavior of stowed tailings before load from the room closure is transferred to it. This showed that there are minimal differences between the creep rate of tailings at different moisture contents, particularly during the first two to three days. Again, note that the same compactive effort was used for all samples and that tailings with 10% moisture content pack somewhat more densely than drier material. Although no other advantages in the control of moisture are apparent from these tests it is important that the behavior of the tailings in a practical stowing situation is also considered. Moisture content may have a considerable influence on the ability of stowed material to remain close to the roof without slumping and this consideration may outweigh that of a small change in stowed density.

5.1.1 Anticipated Room Closures

The ultimate closure of a stowed room due to consolidation of the backfill would be approximately 35% or 1.05 m in a room 3 m high. In addition to this, there is likely to be an additional 0.3 m closure because the stowing machinery will not be able to fill the rooms completely to the roof. Thus, the total closure will be approximately 1.35 m or 45% of room height. The potential surface subsidence caused by mining will be reduced by 55%.

5.2 CREEP TESTS

Samples tested under creep conditions had undergone a consolidation of approximately 22% prior to the start of the test. The creep rate during the tests decreased approximately logarithmically with time and was 0.003% per hour after 25 days. Consolidation during the creep was 9.7% after 14 days and 10.5% after 25 days. Following creep, samples had attained almost 90% of the density of solid rock salt. Thus, a dense, high strength material had been formed once approximately 32% total consolidation had occurred. Consolidation of 35% after 1 year under load would be predicted from the results.

The strength of the extruded samples tends to increase with increasing time under load. From the preliminary tests performed, an ultimate unconfined strength of between 15 MPa and 20 MPa is anticipated. This is comparable to the unconfined strength of a typical rock salt, demonstrating the value of tailings as a backfill material. The modulus of 830 MPa is less than 5% that expected for a solid salt. Oddly, this does not appear to be strength related; that is, it did not increase with an increase in unconfined strength. The microscopic studies of the salt fabric suggest that the bonding between grains which is responsible for the gain in strength of the crept samples is very similar in nature to the bonding of crystals within a solid salt and quite different from the bonding present in agglomerated masses of unconsolidated grains. Thus, given the required 35% closure of the stowed room (more closure would be required if the room

could not be completely filled) it is possible to reform a solid material which is likely to have properties which are extremely similar to the materials surrounding it. This would appear to have distinct advantages when planning future strata control measures as the response of the stowed room would be similar to that of solid salt under the same stress field.

A subjective study of the fabric of crept specimens indicates that pore spaces have good interconnection and that pore pressure build-up during consolidation is unlikely. Following the creep tests the moisture content was considerably below that required to saturate the sample and drainage took place throughout the tests. Brine permeability tests of samples of various ages along with pore pressure measurement during creep would be necessary to provide conclusive information regarding the ability of the salt to drain adequately during the later stages of consolidation. It appears, however that excess pore pressures are unlikely to be formed during consolidation. Studies by RE/SPEC Inc. (Pfeifle et al 1984) support the view that consolidated salt remains free draining for a considerable period.

5.3 TRIAXIAL COMPRESSIVE STRENGTH TESTS

Crushed tailings consolidated under quasi-static loading behave in a way unlike even the weakest natural rock material when tested under triaxial load conditions. (See Figures 4-12 and 4-13). It is postulated that this behaviour is a result of the extremely weak bonding between grains which allows a general failure throughout the sample rather than a localized shear failure. The sample then behaves as a mobile granular mass which is apparently frictionless.

The practical implication of this behaviour is that under conditions where the roof load is applied very quickly the backfill is liable to squeeze out of the opening rather than become well consolidated and develop high unconfined strength. Tailings which were consolidated under confined creep conditions were not tested triaxially so it is not certain whether their behaviour is substantially different. While some creep of well-consolidated tailings is inevitable it is not anticipated that flow

would be at the high rate observed for quasi-statically consolidated samples. In order to achieve this high degree of consolidation it may be necessary in some areas to provide bulkheads of stiffer material to contain the tailings until they have gained adequate strength. This bulkhead could take the form of tailings mixed with an additive such as cement which would harden relatively rapidly. This situation can be forseen at the entrance to mined rooms where it is necessary to prevent backfill squeezing out into roadways and ventilation tunnels. Drainage of the backfill behind the bulkhead would require placing piping or drainage material below or through the cemented fill.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONSOLIDATION OF CRUSHED SALT TAILINGS

a) Moisture content has a distinct effect upon the ability of crushed salt tailings to pack closely during compaction. Although no difference in behavior is observed between 0% and 5% moisture content, at 10% moisture content the packed sample is 5% more dense. While dry density after packing may increase with continued increase in moisture content it is difficult to prevent brine leaving the system and higher moisture contents are unlikely to have much practical application.

b) The dry density at maximum load during quasi-static consolidation is not dependent upon moisture content. Final density appears to be a function of maximum load alone.

c) As a result of closer initial packing, samples with 10% moisture content were less compressible than those with lower moisture contents. For example, at 25 MPa maximum stress, samples with a moisture content under 5% consolidated 4 percent more than samples with 10% moisture content.

6.2 CREEP BEHAVIOR

During creep at a stress of 25 MPa the salt tailings rapidly achieve a strength similar to that of rock salt. Approximately 32% strain is necessary to develop an unconfined strength of 15 MPa. Moisture loss is accompanied by reprecipitation of salt at grain contacts and growing together of adjacent grains to form a matrix of solid salt having smaller salt grains and brine within the pore spaces. The process produces a matrix which is visually similar to natural rock salt.

Short term creep tests indicate that the initial moisture content of the tailings has a negligible influence on creep behavior. This presumably results because samples drain to a moisture content below 5% during quasi-static loading so that moisture contents are essentially similar once the creep phase begins.

6.3 STRENGTH OF CONSOLIDATED TAILINGS

Following quasi-static consolidation a weak, friable material is formed which possesses no unconfined strength unless the maximum consolidation pressure is greater than 14 MPa. Even at pressures up to 35 MPa unconfined strength is very low unless some period of creep is allowed. Strength is probably as much due to mechanical interlock of the grains as to reprecipitation or intergrowing of crystals. Under triaxial loading conditions samples gain strength for confining stresses up to 5 MPa but yield at a constant deviator stress thereafter. This behavior indicates that at higher confining pressures the samples do not fail by shearing but deform in a plastic fashion and becoming apparently frictionless. This behaviour at much higher stresses, is common of many geologic materials.

One implication of this behavior is that unless the tailings can be confined while creep consolidation occurs, it is possible that the backfill may be squeezed out of the stowed opening as closure takes place.

6.4 RECOMMENDATIONS

During the course of this study it has been possible to identify several areas of tailings behavior which merit further research. In order of the importance which it is felt they deserve, these are:

1) Further study of the strength of tailings consolidated under creep conditions. This should include triaxial strength tests on samples consolidated under various loads and for several different time periods. Adequate knowledge of the mechanical properties of the consolidated tailings will be required for safe and economical mining, particularly in the application of numerical methods to mine design.

2) Permeability studies. The variation in brine permeability during consolidation is important both in predicting the behavior of the consolidating fill and in assessing its value as a bulkhead material preventing inflows to the mine.

3) The use of additives in tailings. Where rapid strength development and roof support are required the addition of additives such as cement, clay, lime or fly ash might be considered. The design of economical combinations of salt and additive will require extensive experimental work prior to field trials. This study is an extension to the basic work on salt behaviour which should be implemented once a firm committment to begin stowing with tailings has been made.

ACKNOWLEDGMENT

This report has been prepared under a contract from the Canada Centre for Mining and Energy Technology. The author is grateful to Mr. Marc Bétournay, Scientific Authority, for his encouragement and helpful advice. Both the experimental work and the final report have benefited greatly from the discussions with and review by Dr. Hans Y. Tammemagi. Facilities of the University of Calgary were used for a large part of the laboratory testing and the technical staff of the Department of Civil Engineering provided valuable assistance. Finally, the author is grateful to Mrs. Barbara Stein for typing the manuscript.

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APPENDIX A

QUASI-STATIC CONSOLIDATION CURVES

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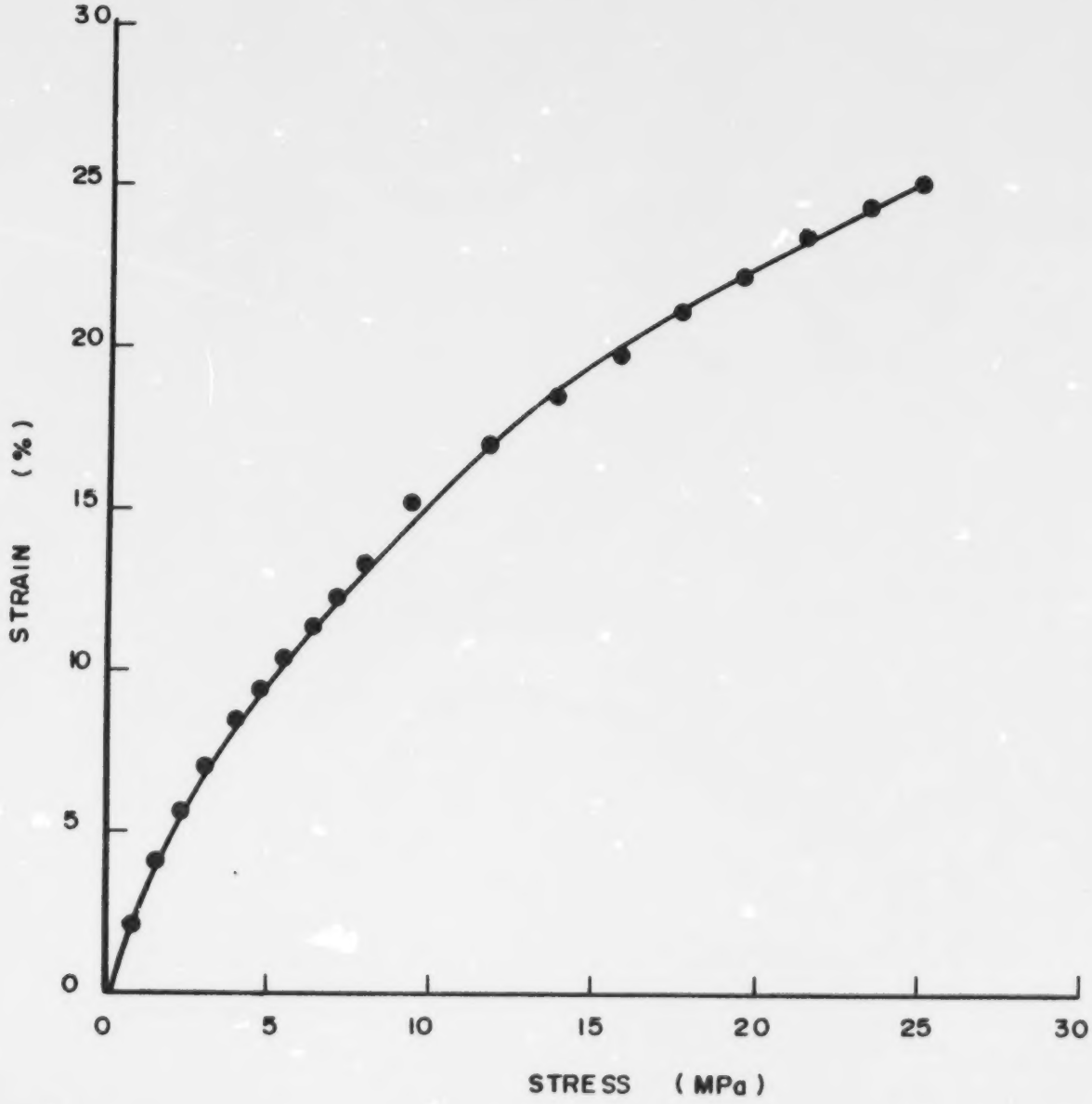

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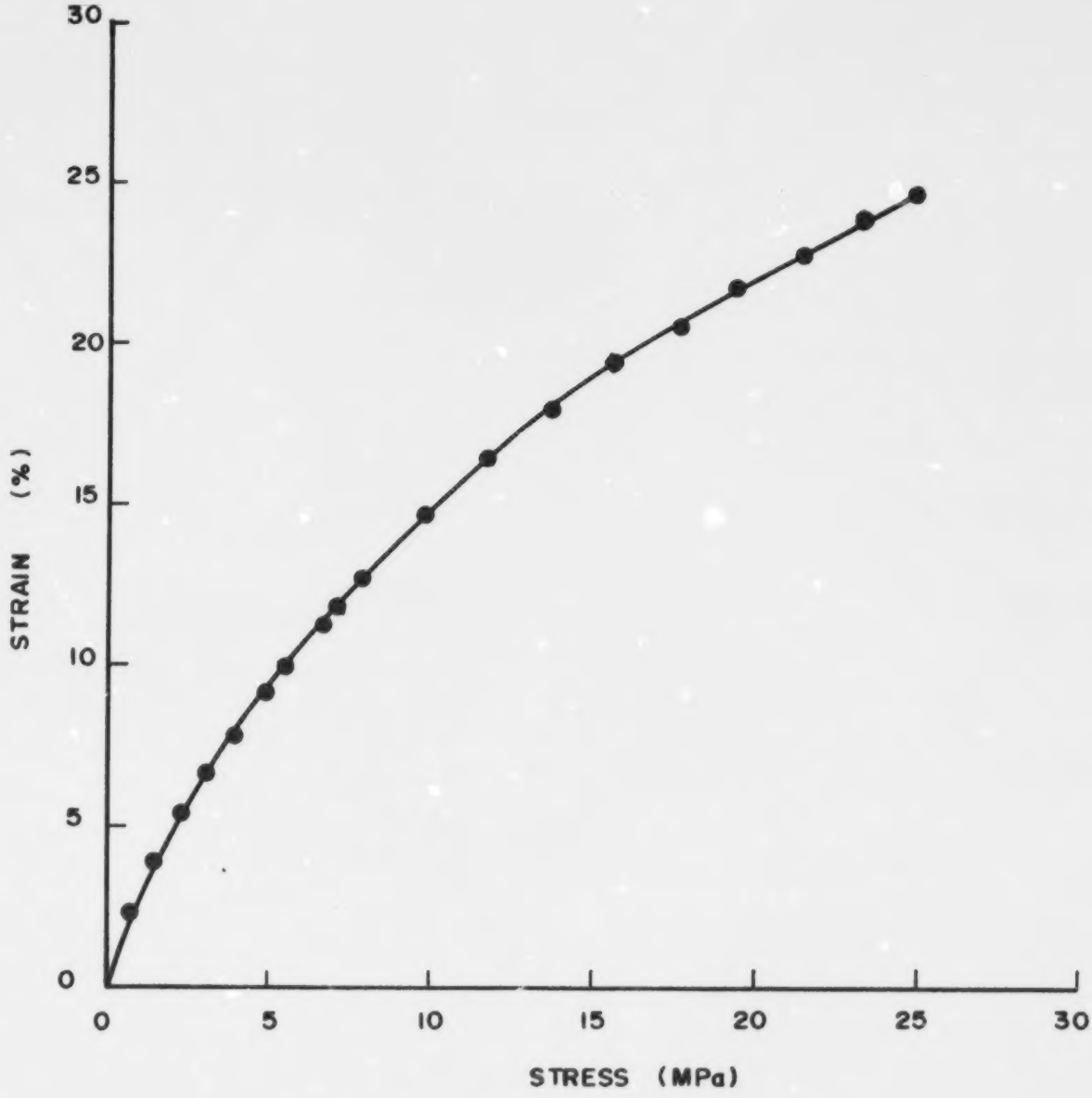

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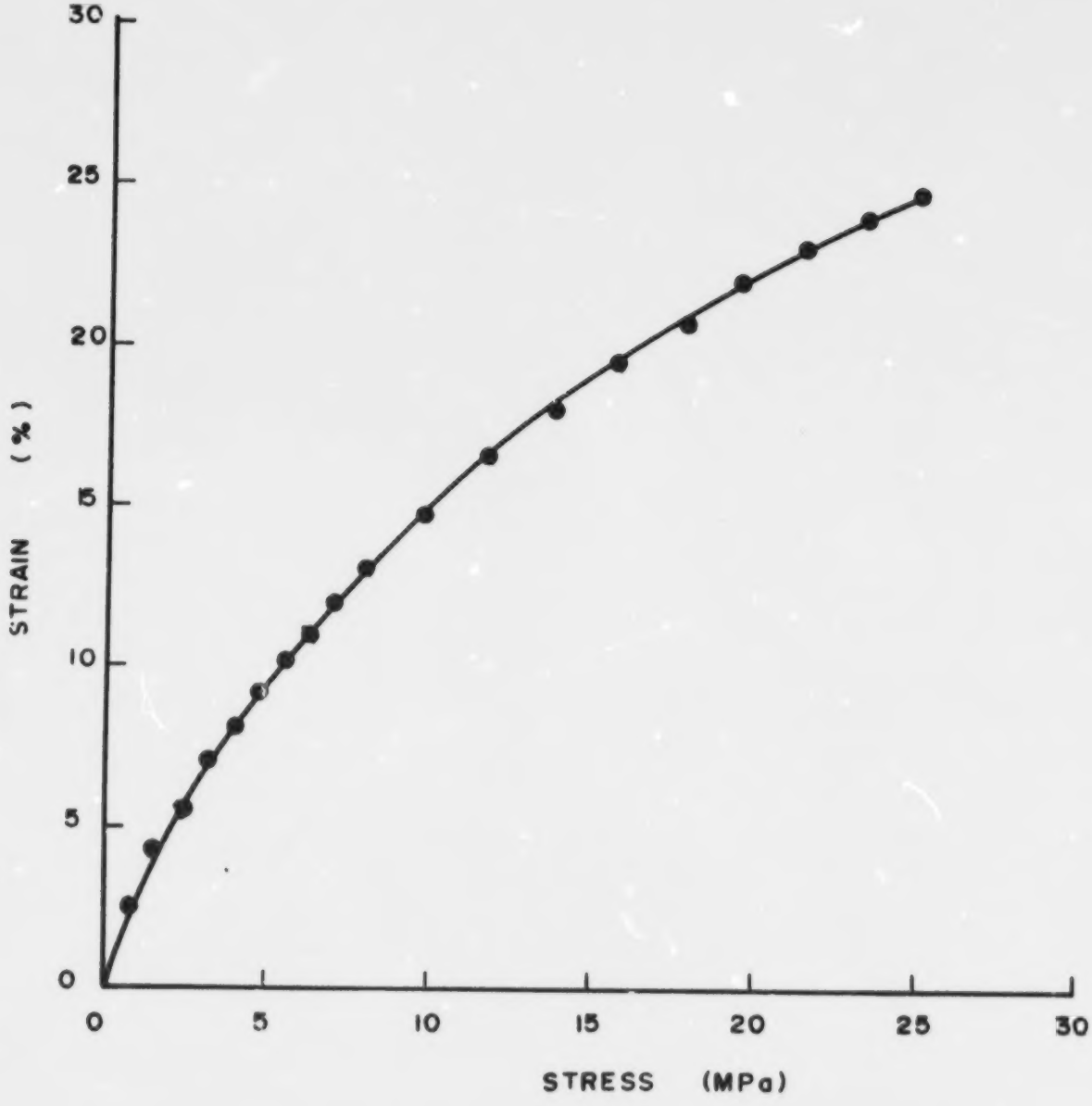

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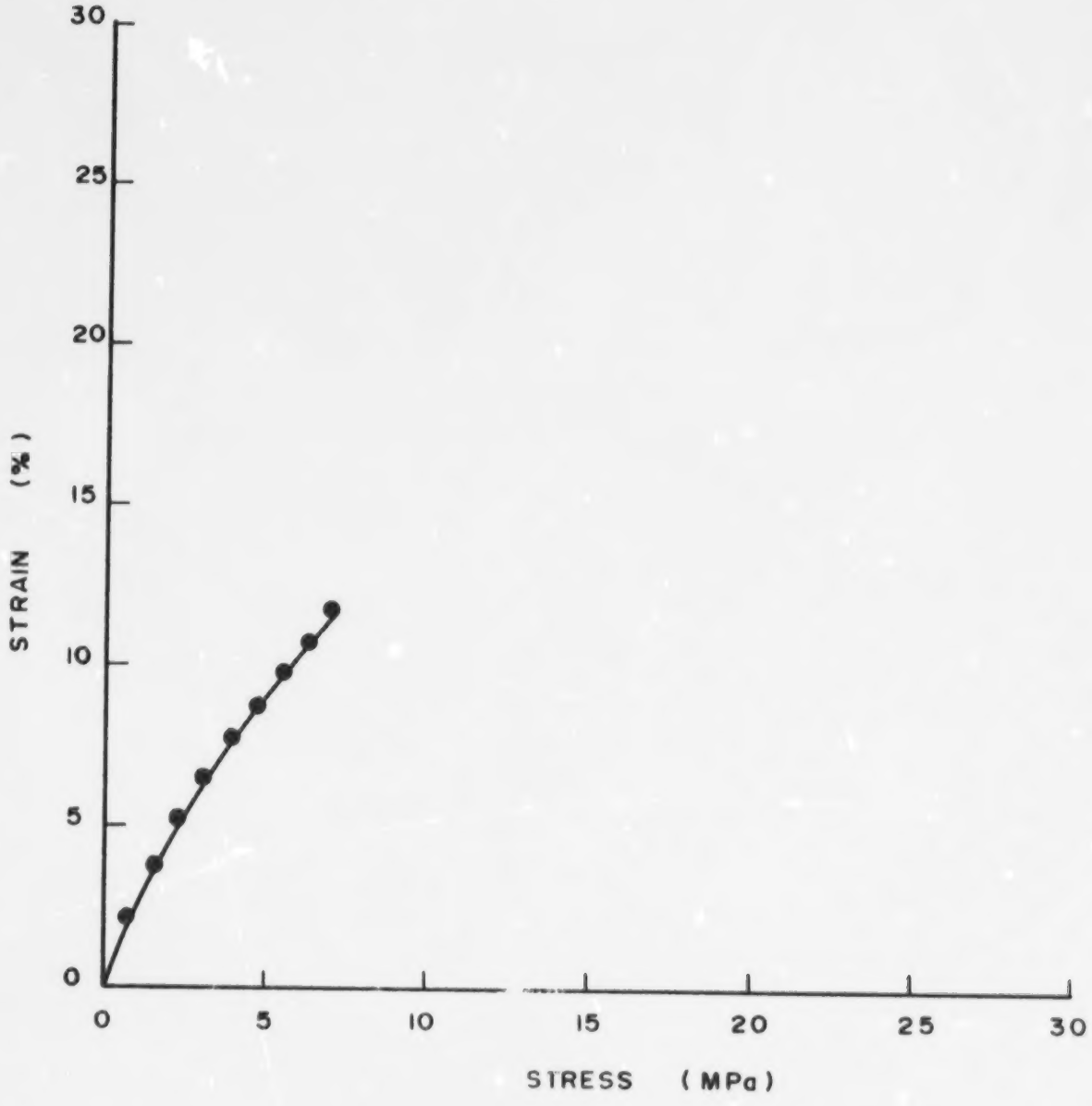

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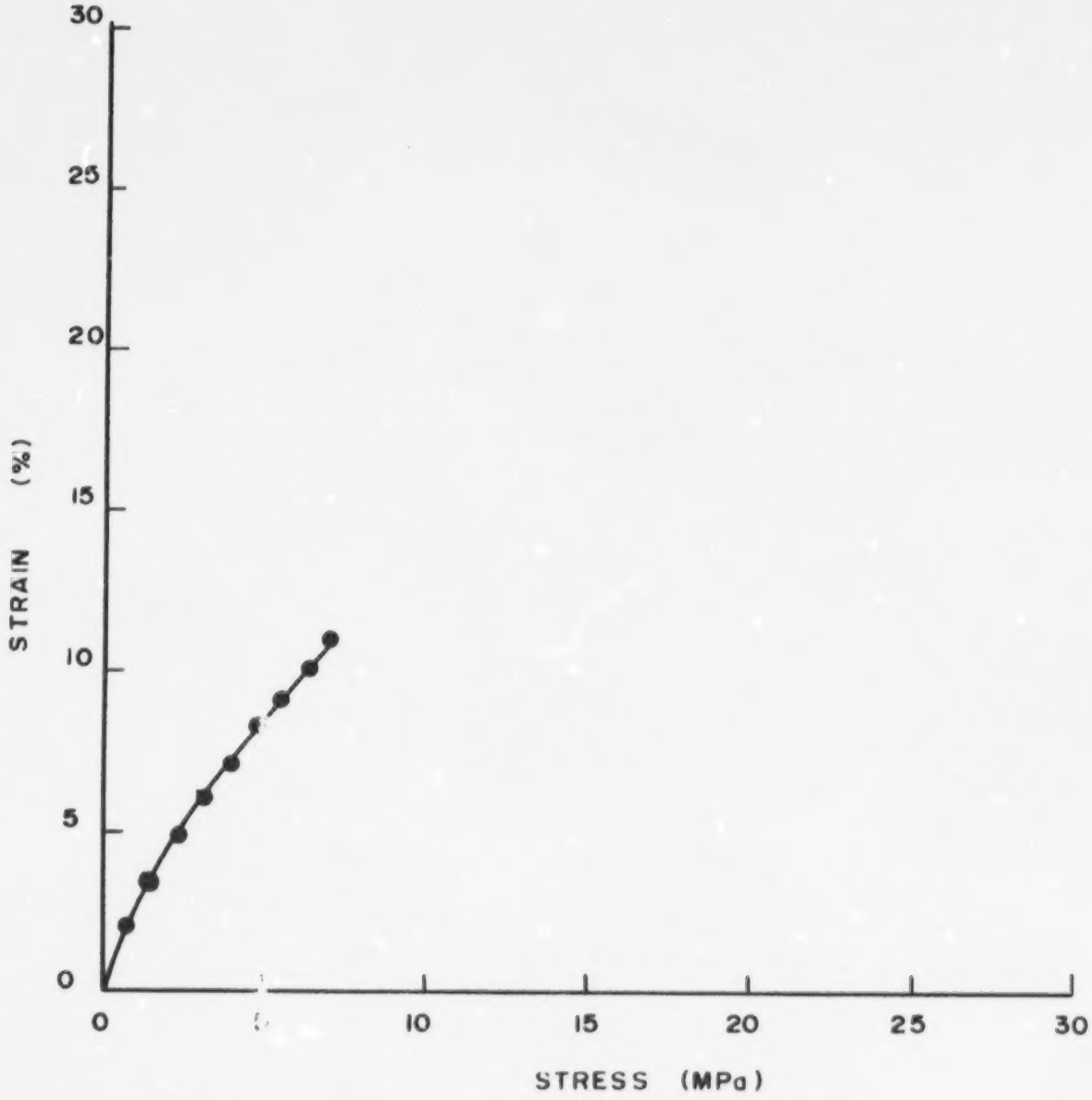

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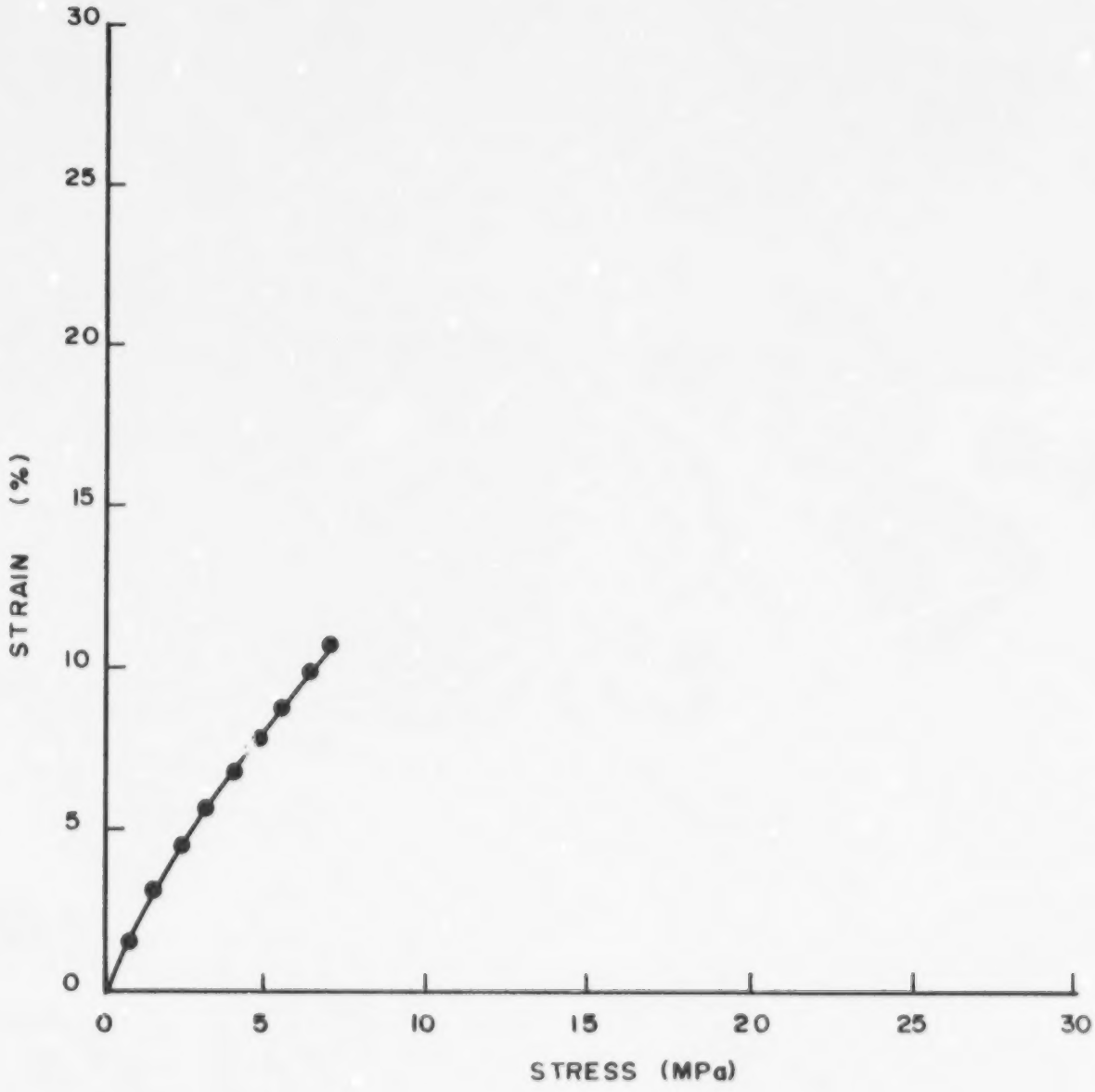

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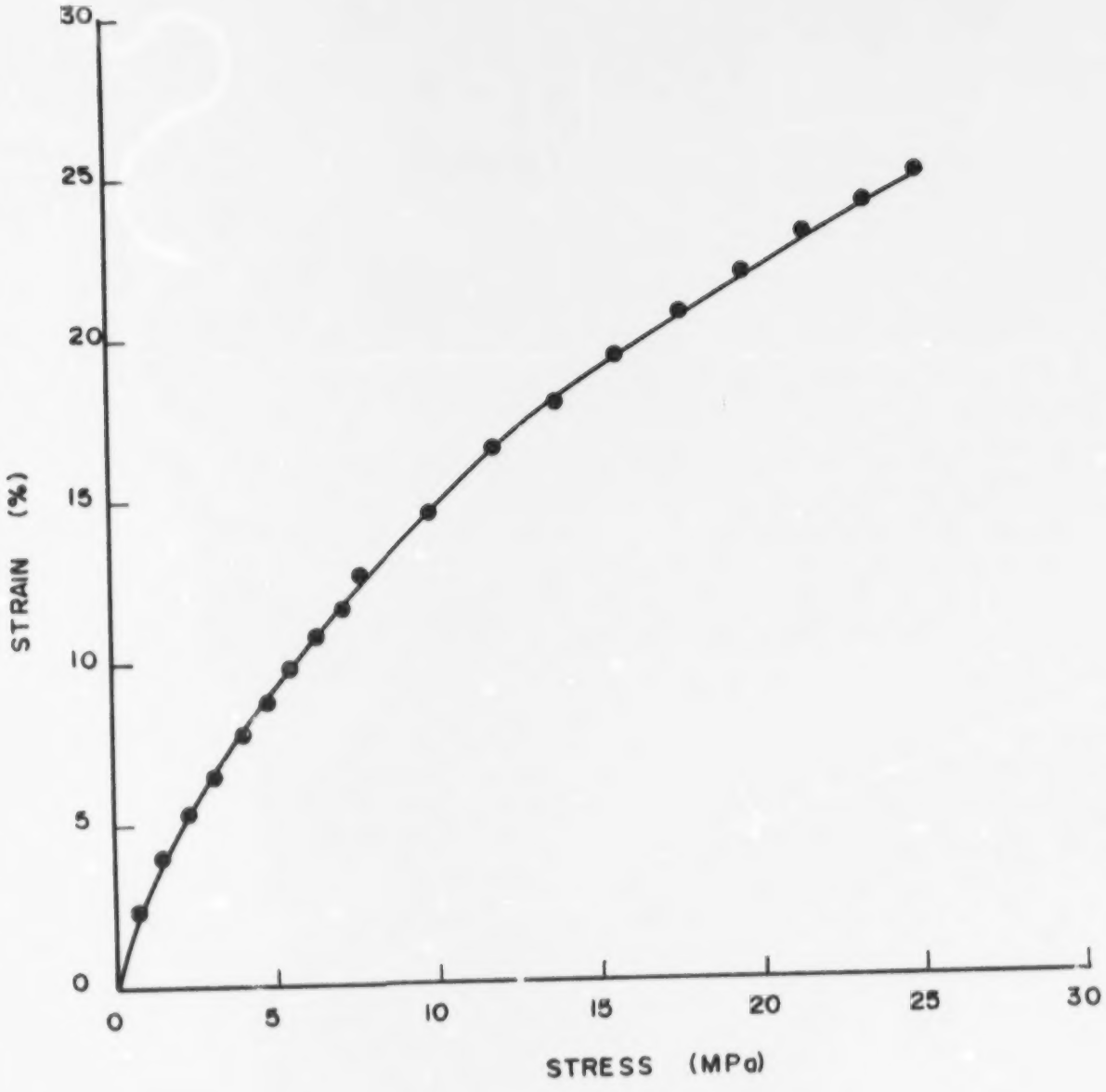

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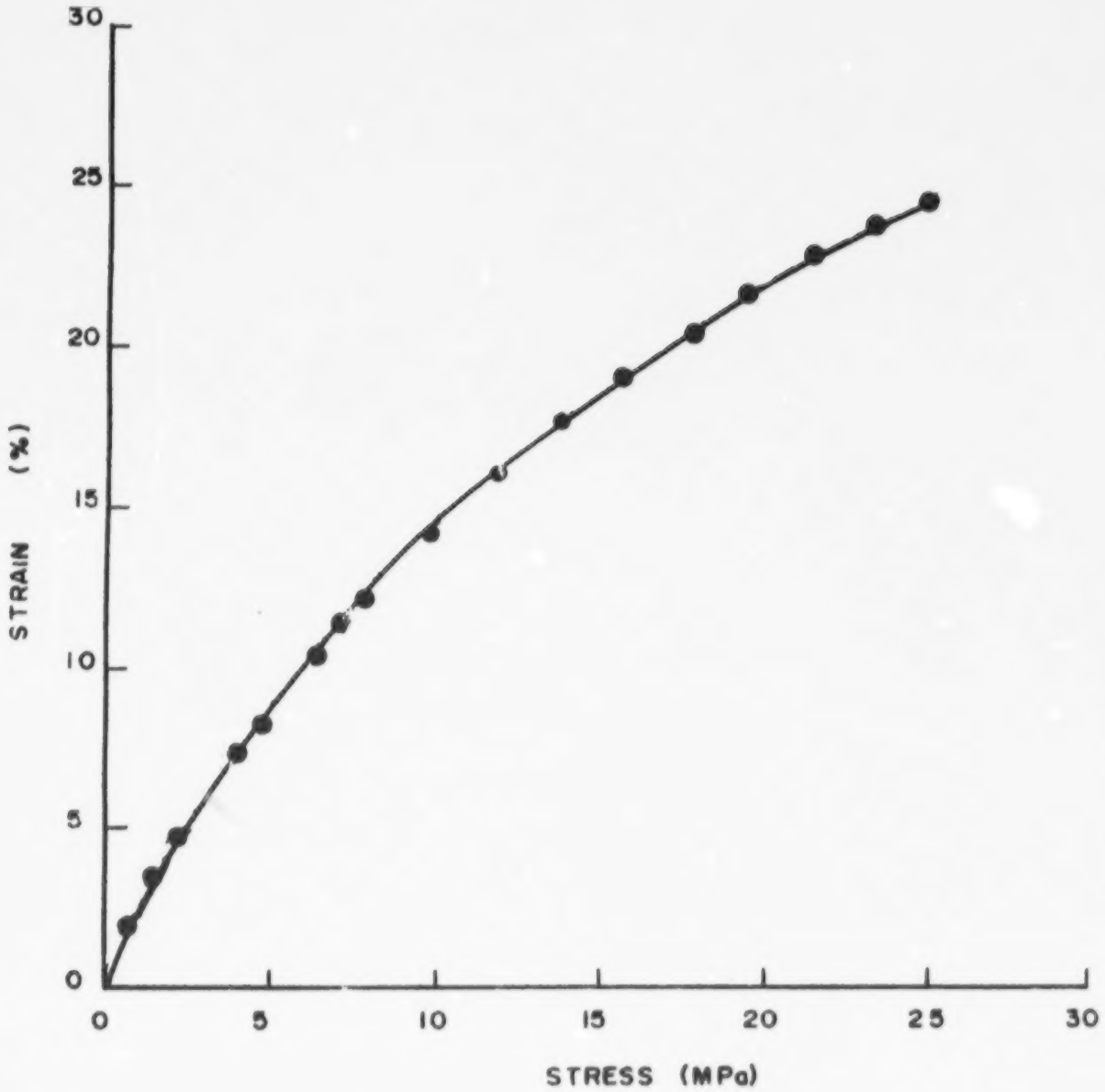

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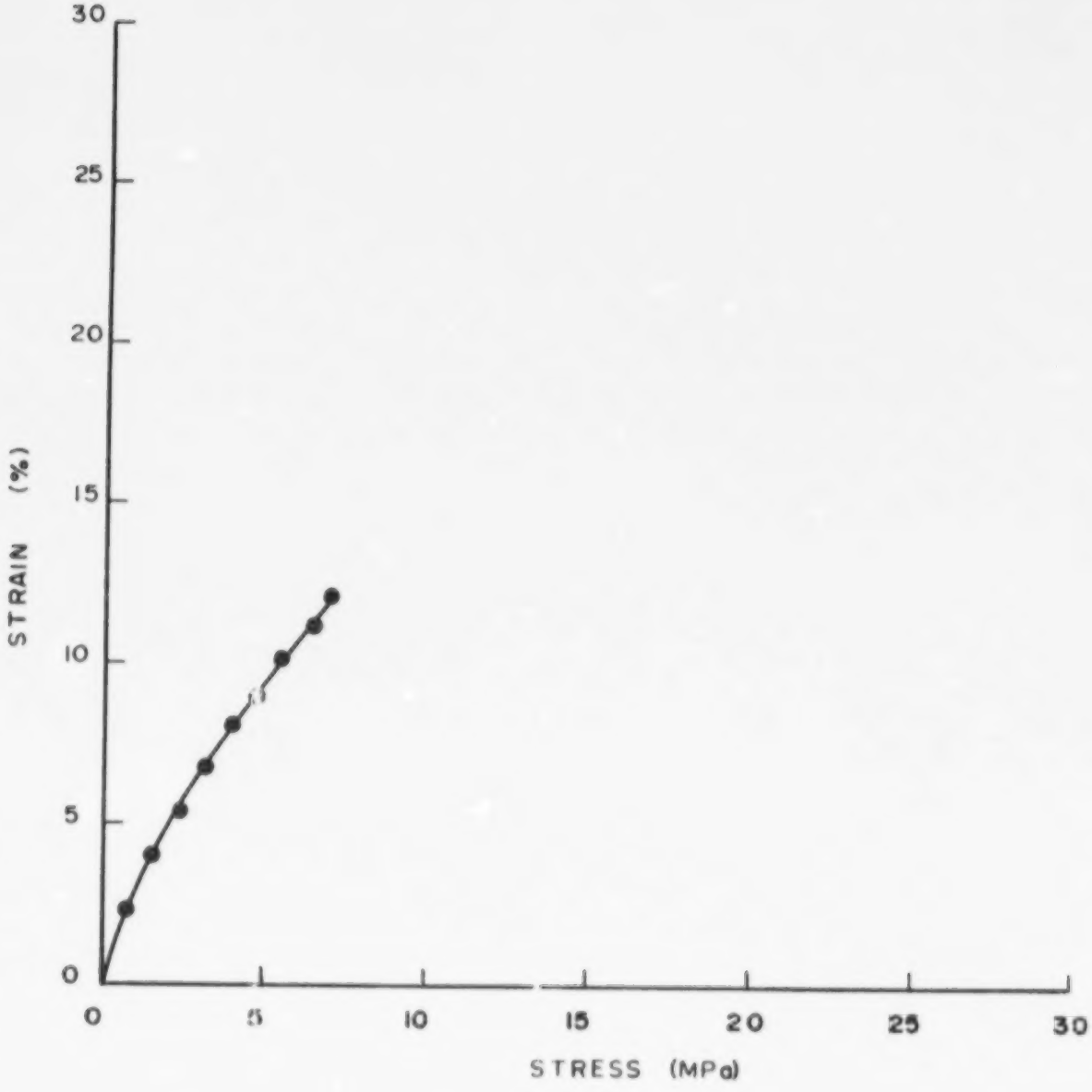

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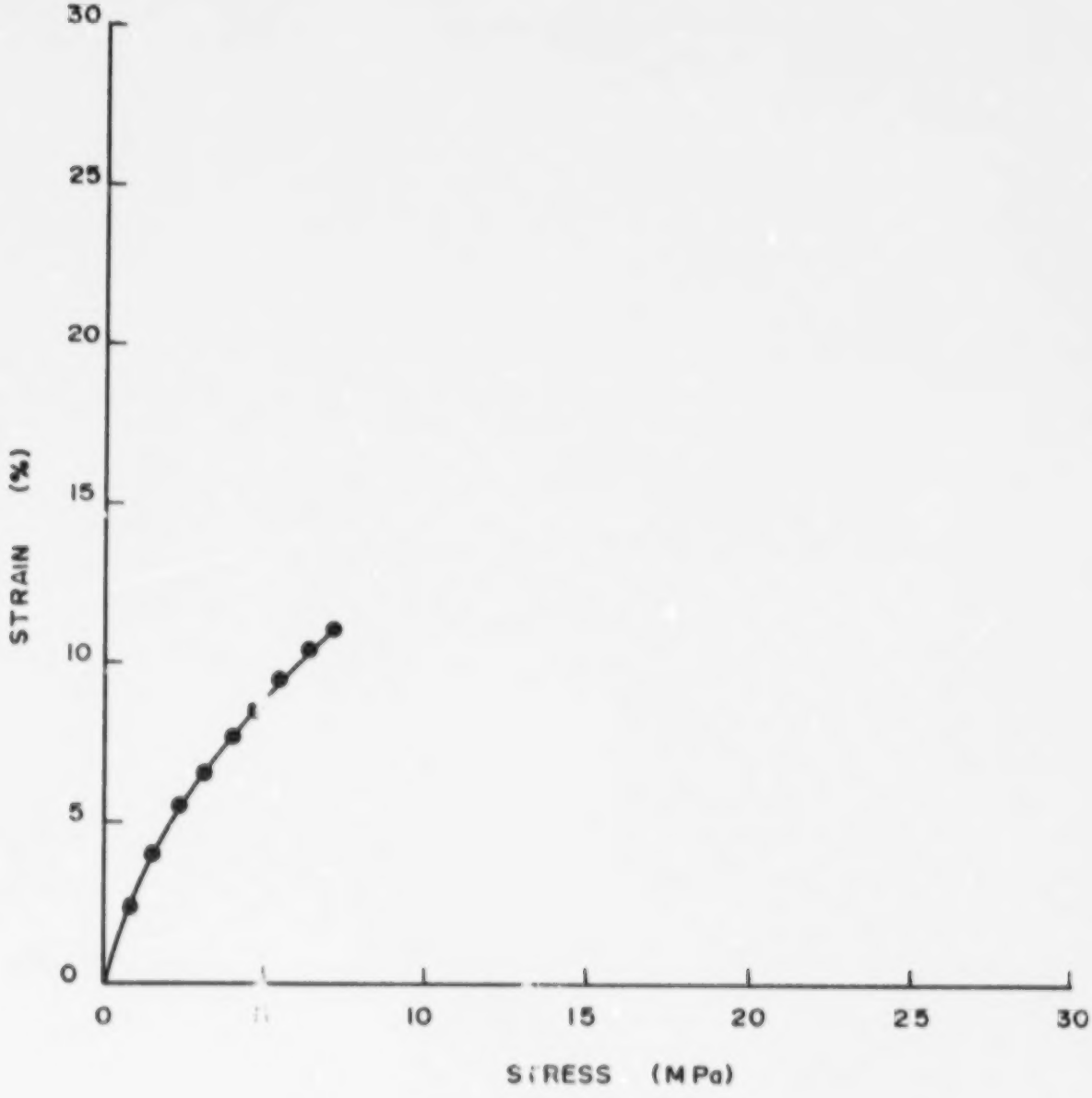

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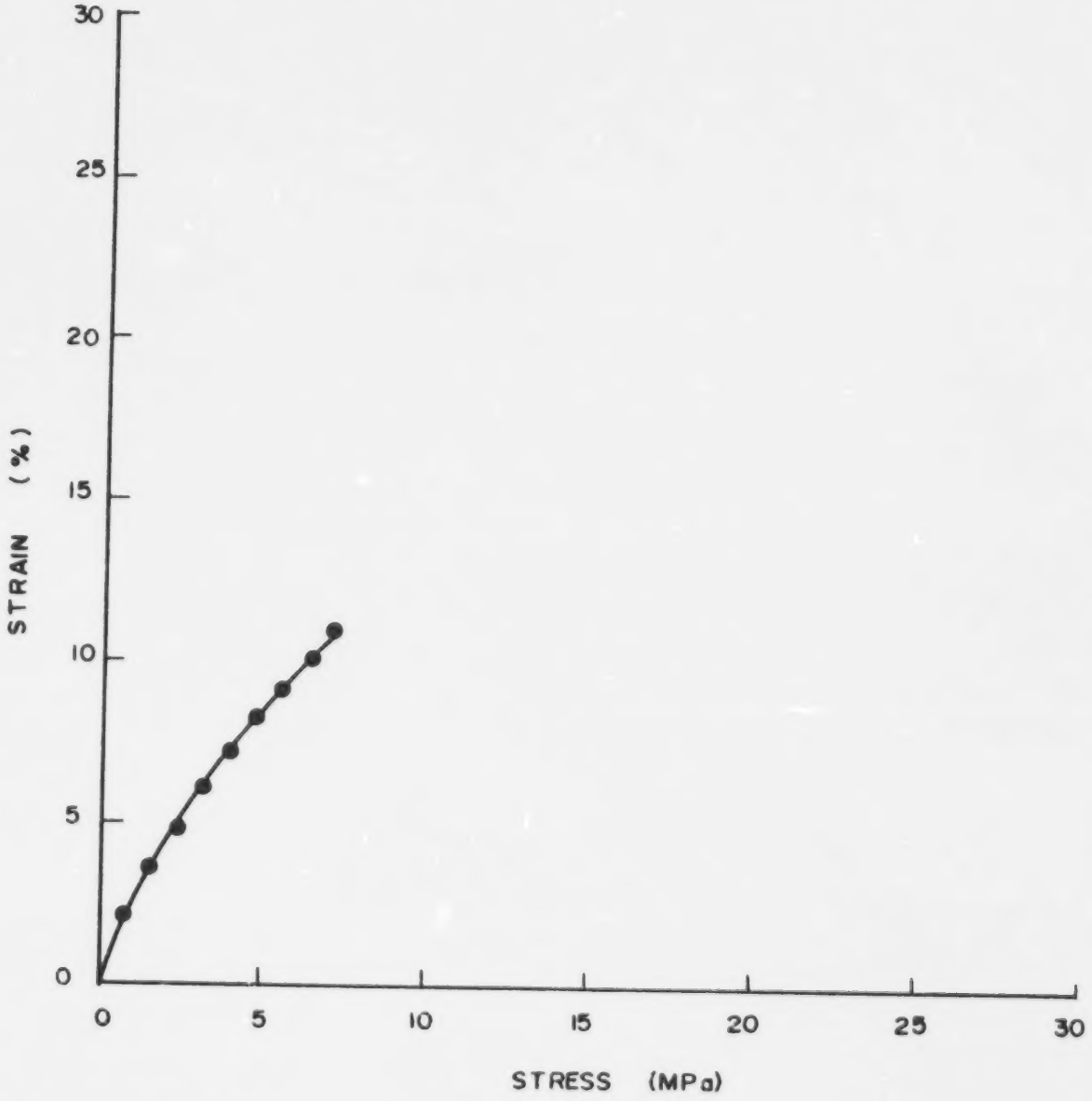

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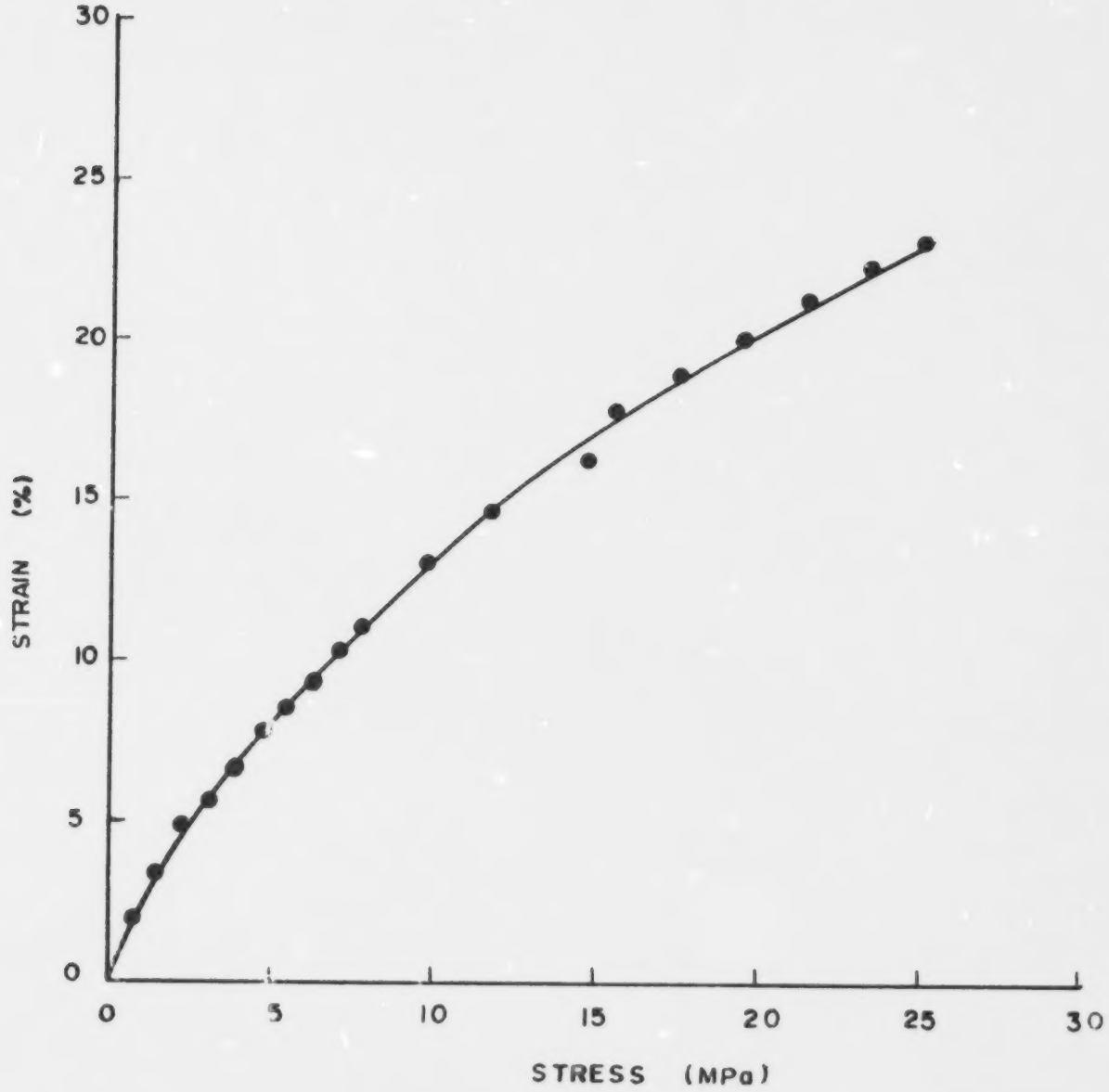

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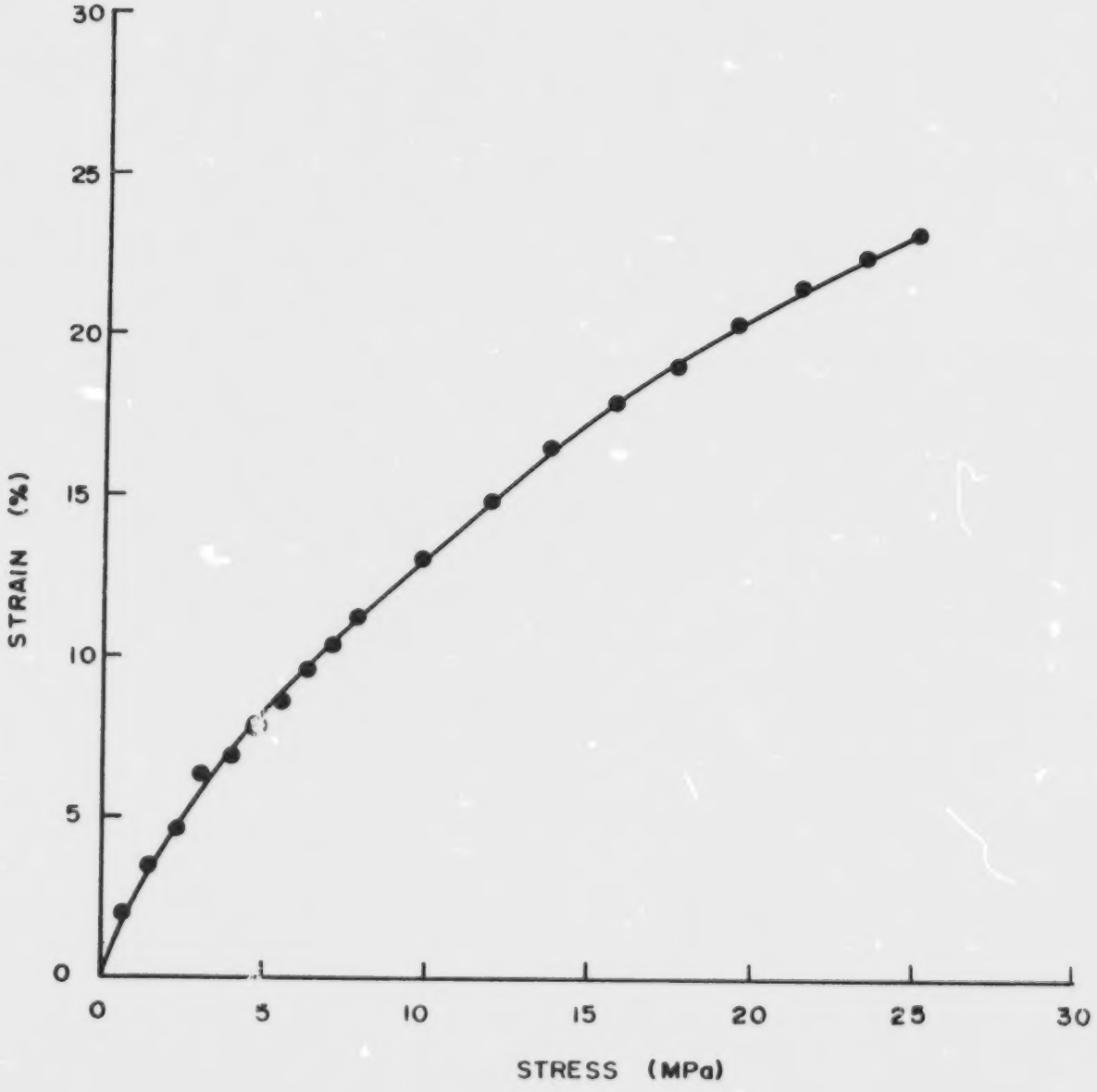

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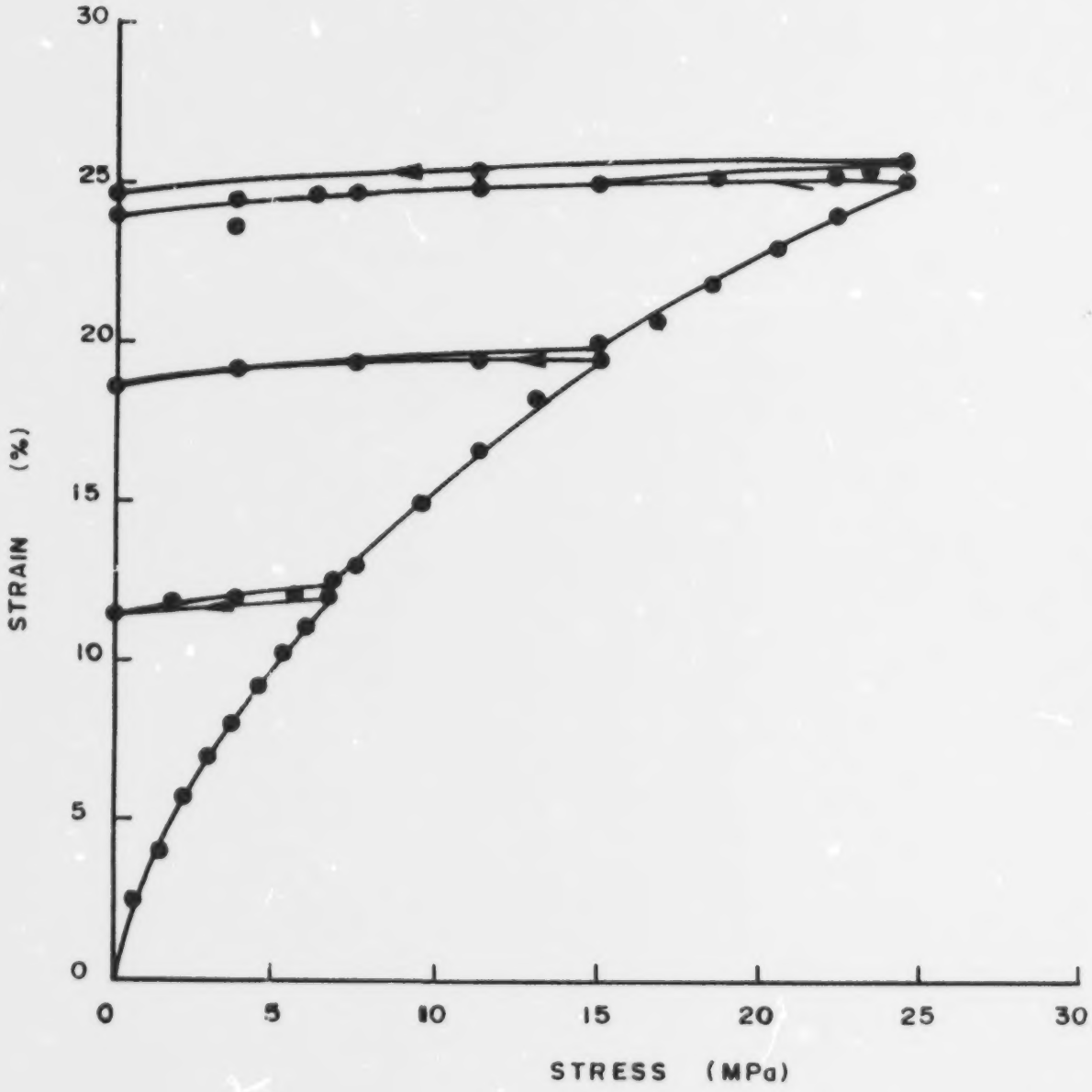

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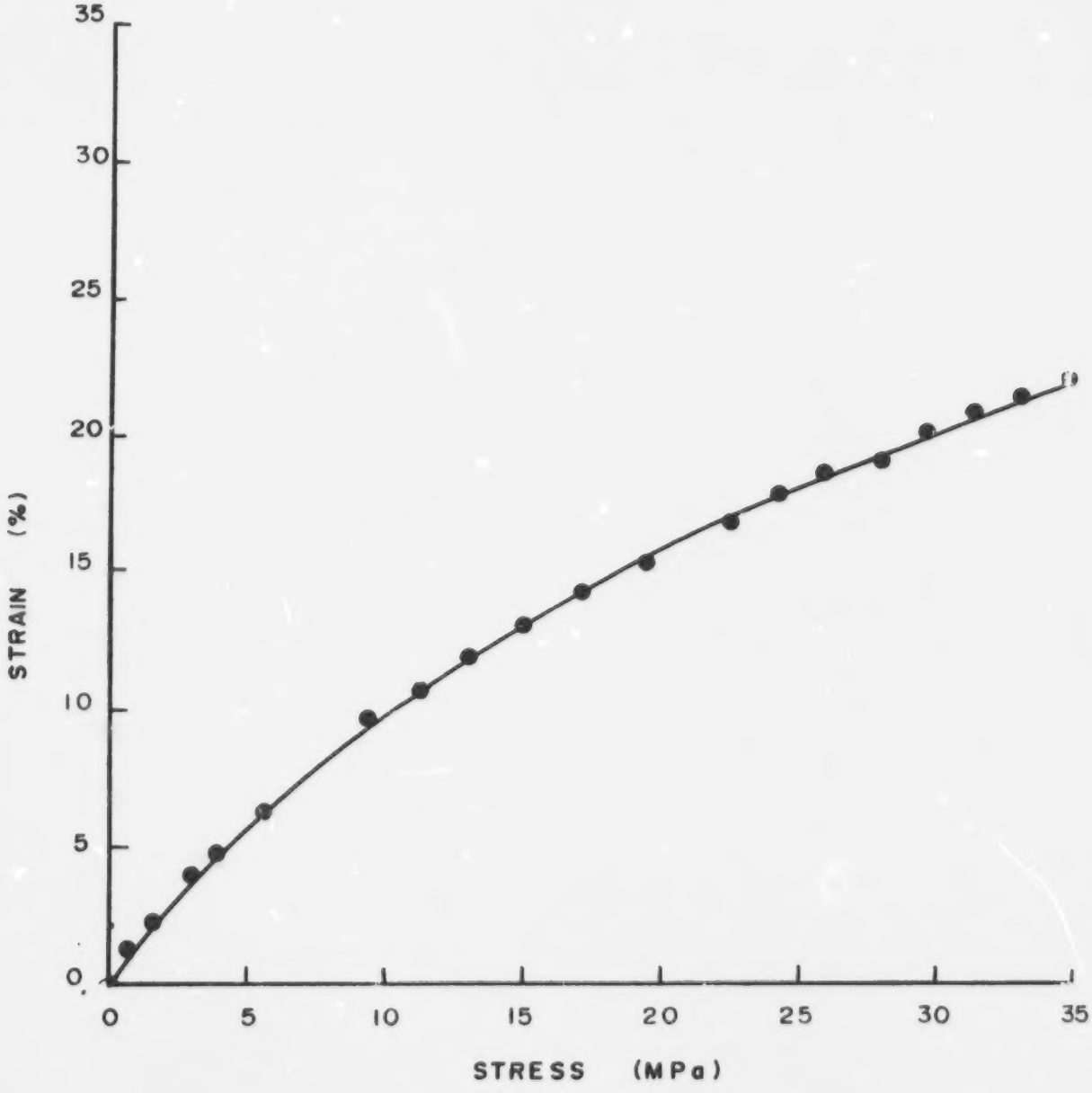

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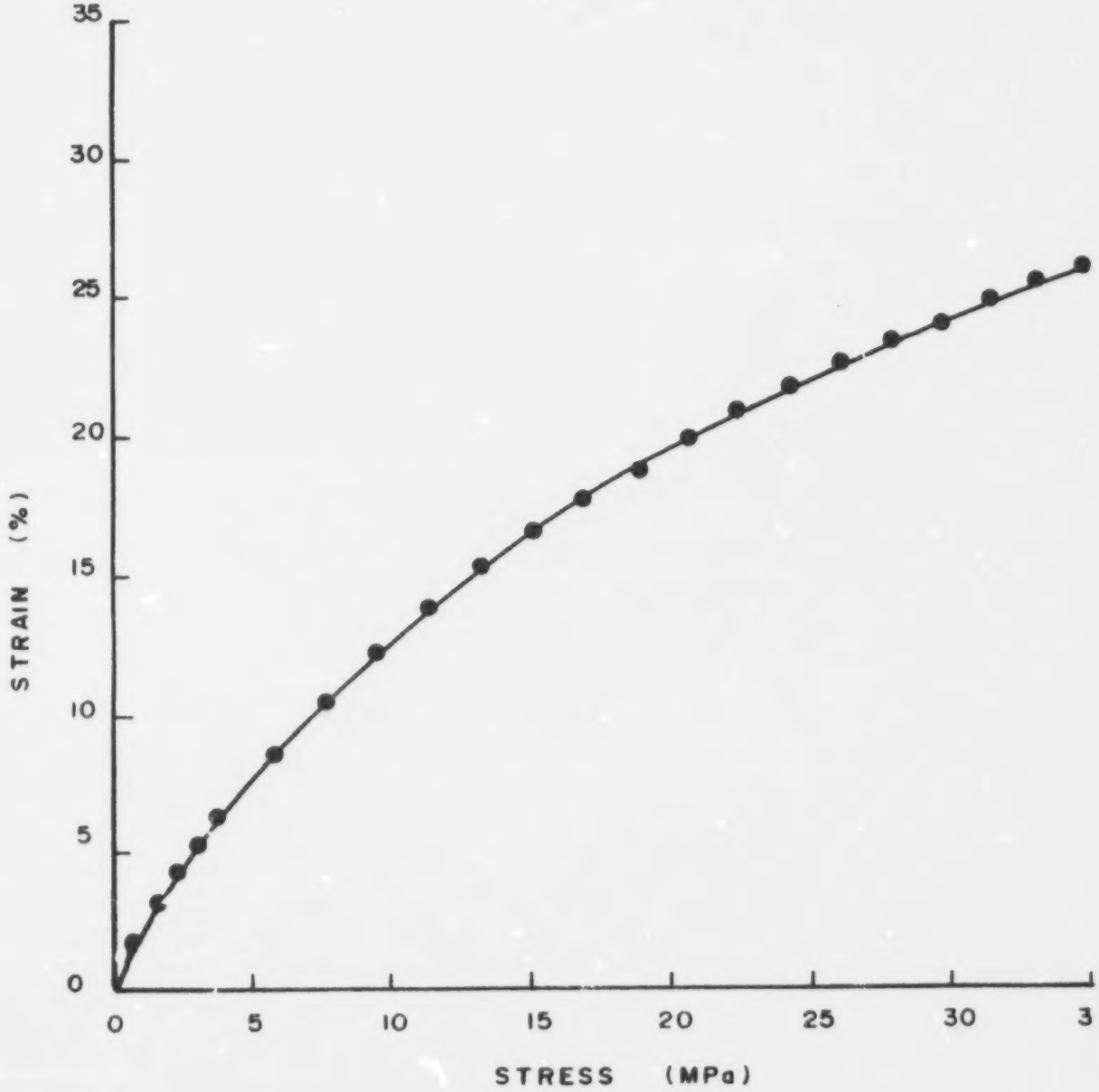

Figure A-16. Quasi-Static Consolidation Test Number 16

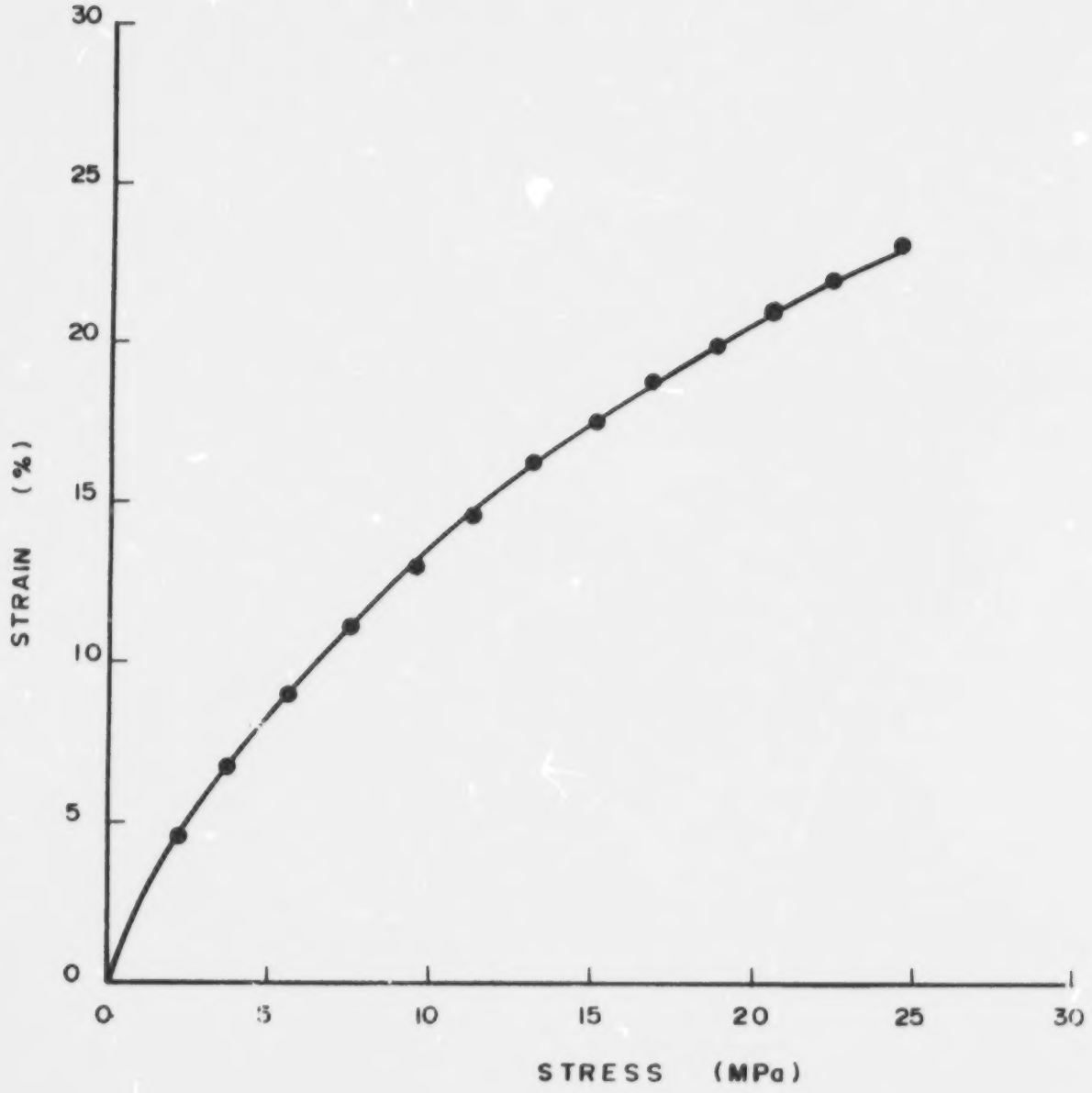

Figure A-17. Quasi-Static Consolidation Test Number T 01

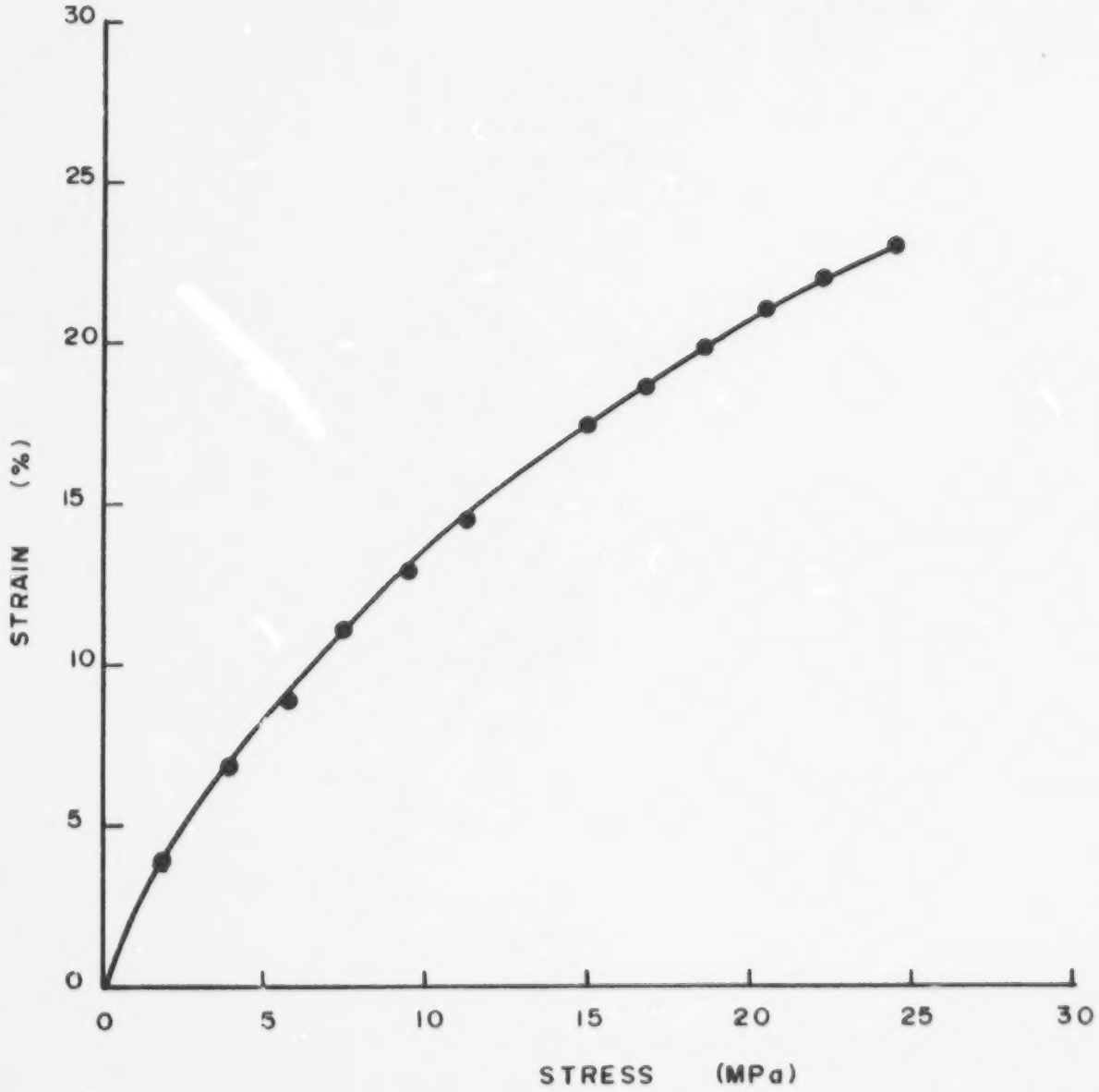

Figure A-18. Quasi-Static Consolidation Test Number T 02

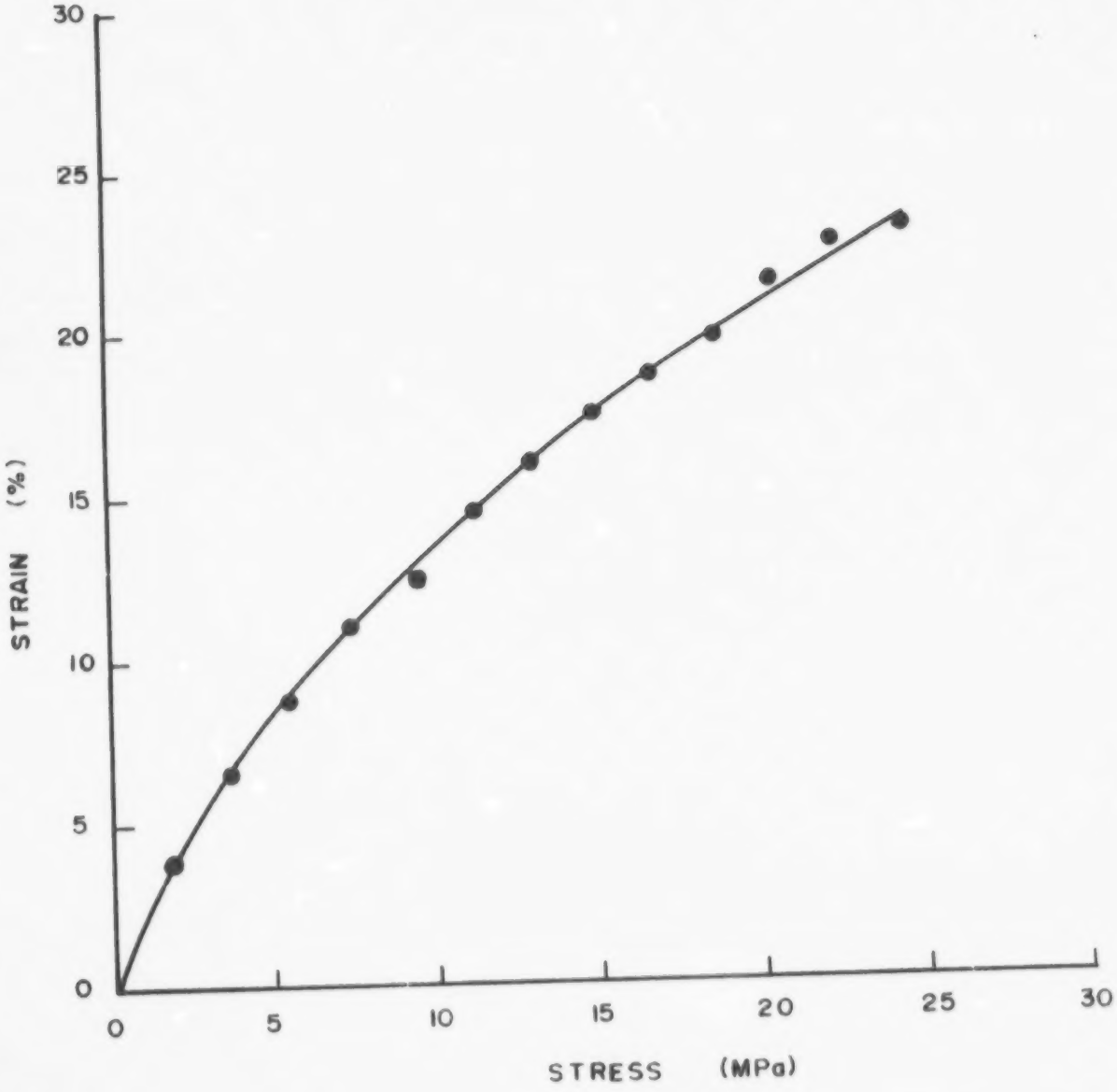

Figure A-19. Quasi-Static Consolidation Test Number T C3

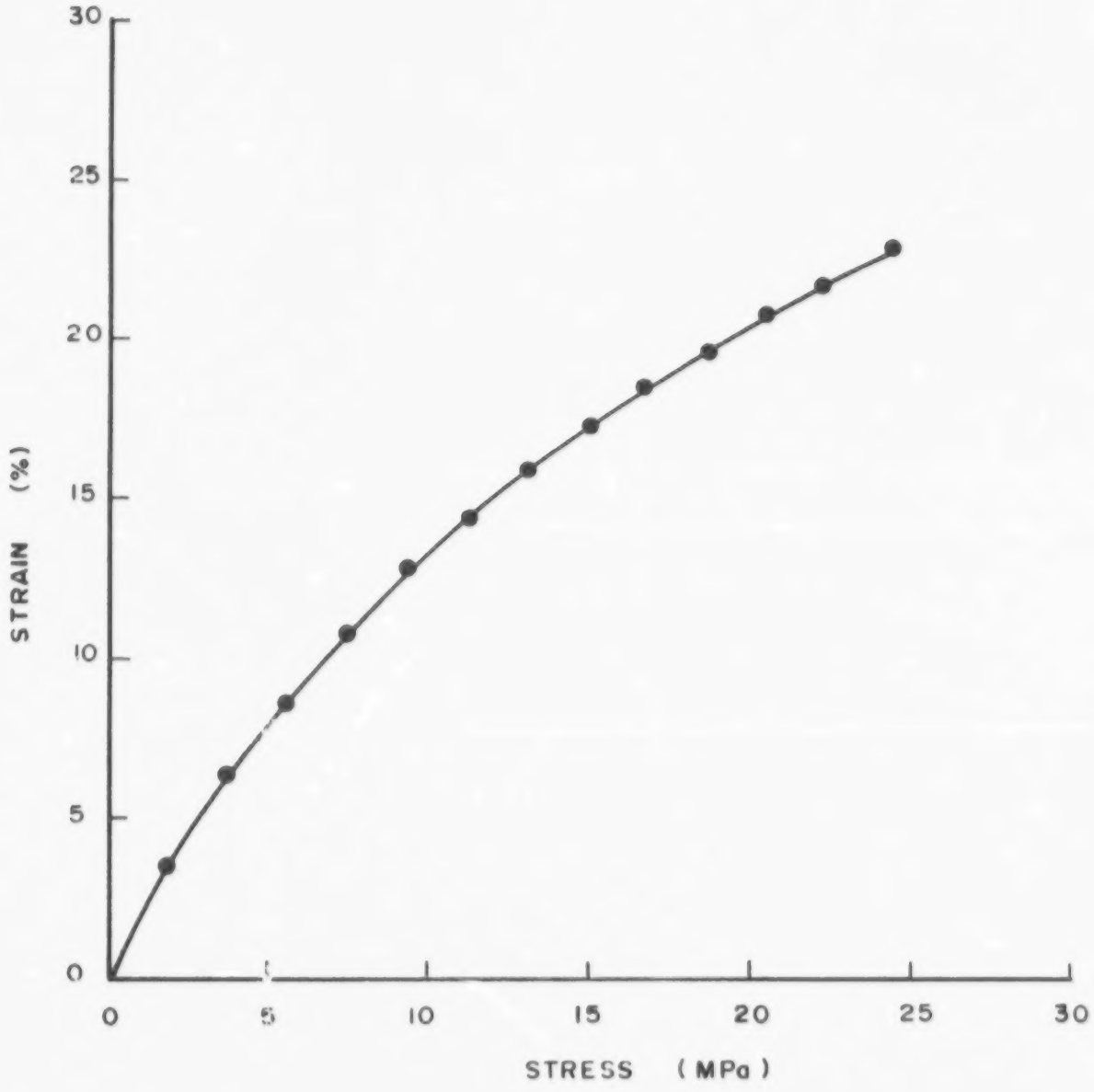

Figure A-20. Quasi-Static Consolidation Test Number T 04

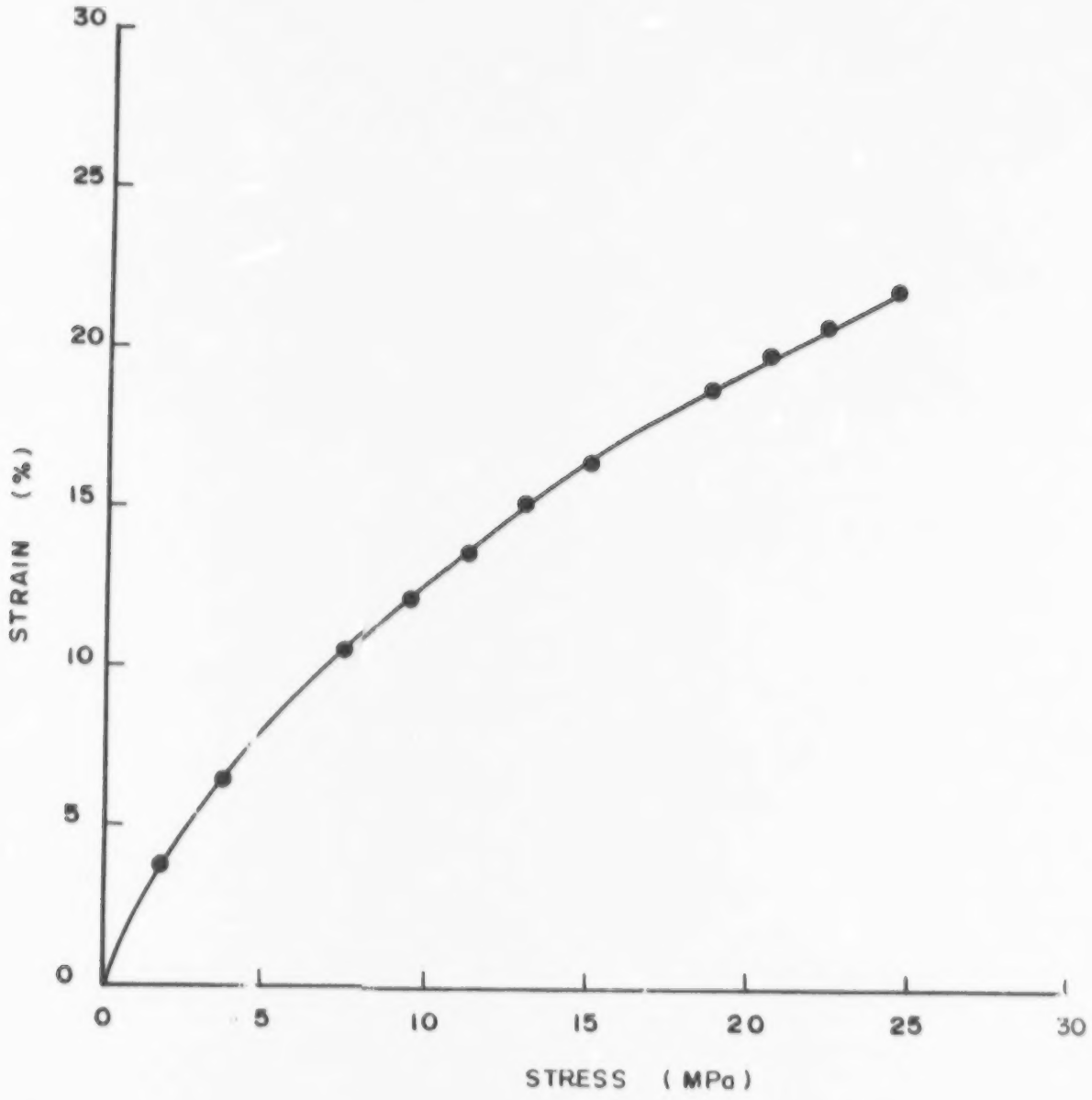

Figure A-21. Quasi-Static Consolidation Test Number T 05

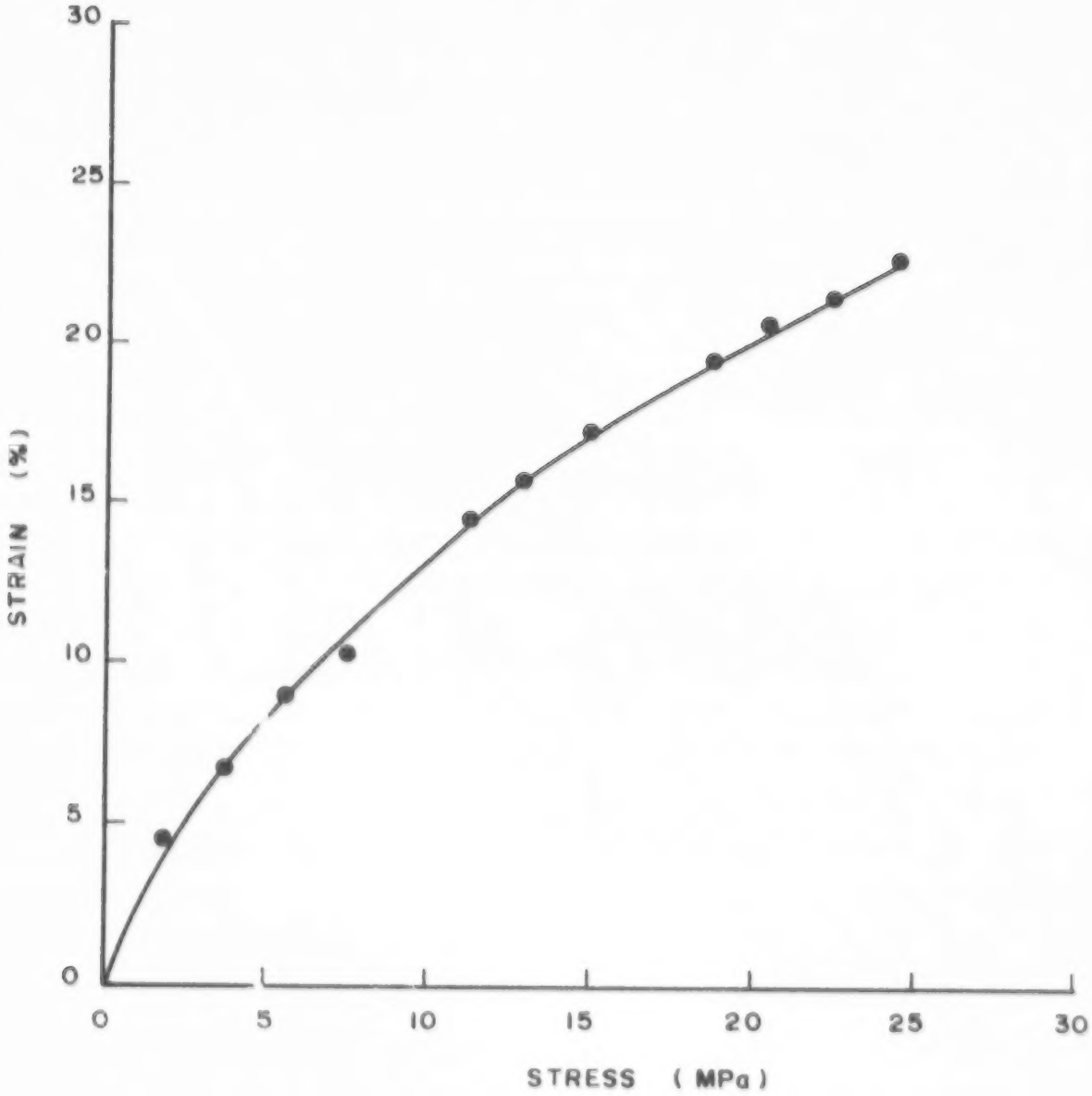

Figure A-22. Quasi-Static Consolidation Test Number T 06

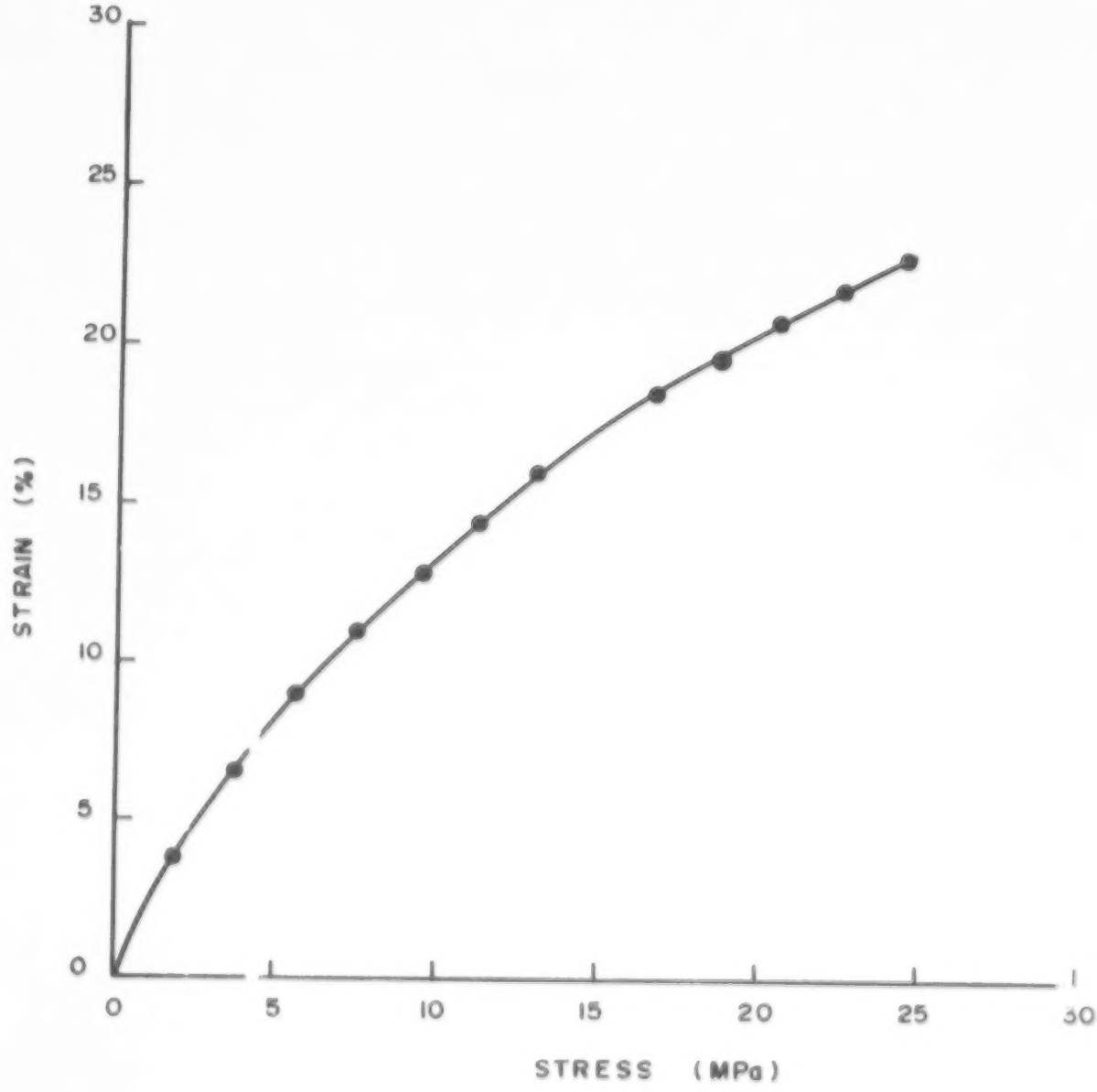

Figure A-2:. Quasi-Static Consolidation Test Number T 07

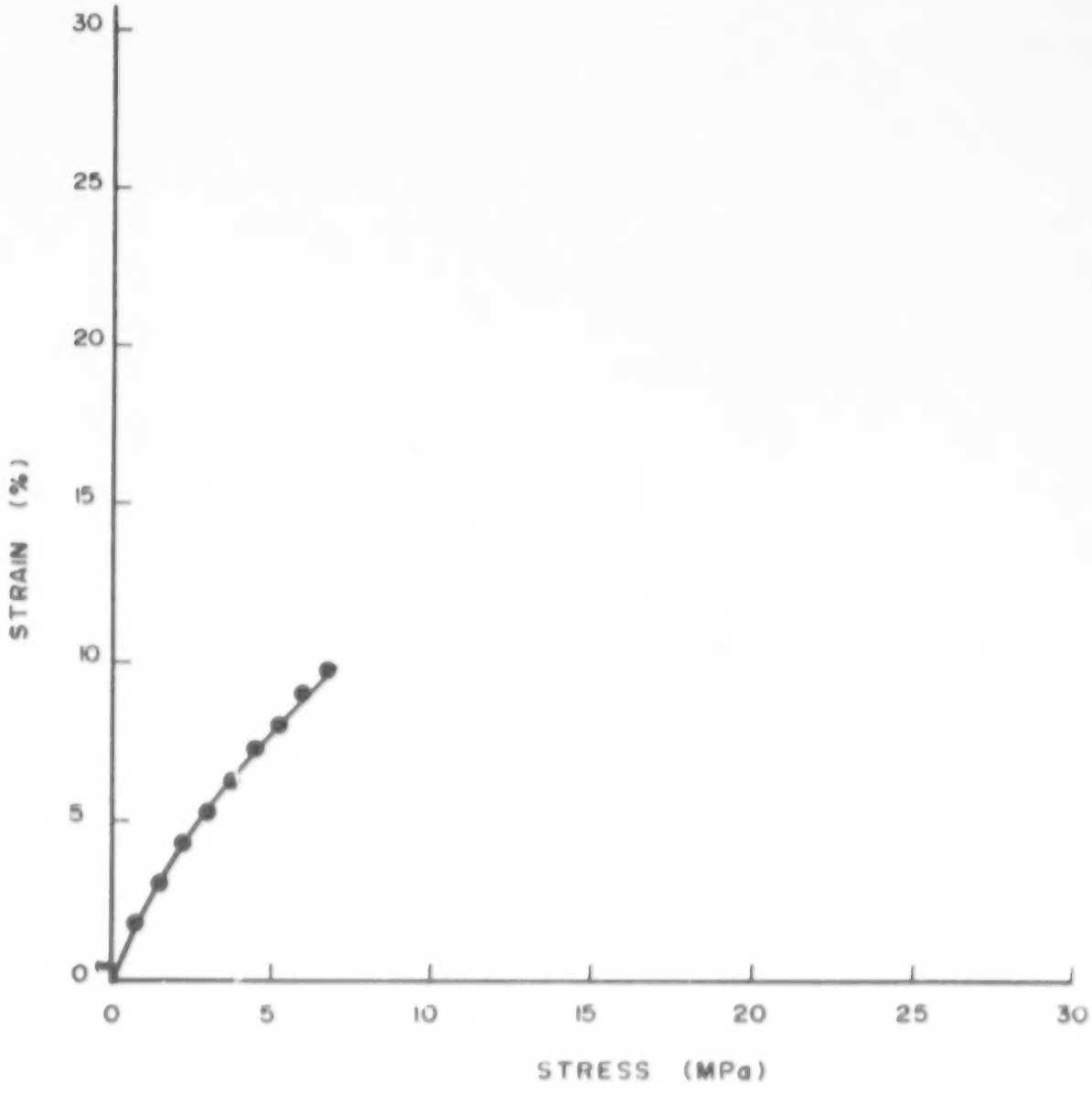

Figure A-24. Quasi-Static Consolidation Test Number T 08

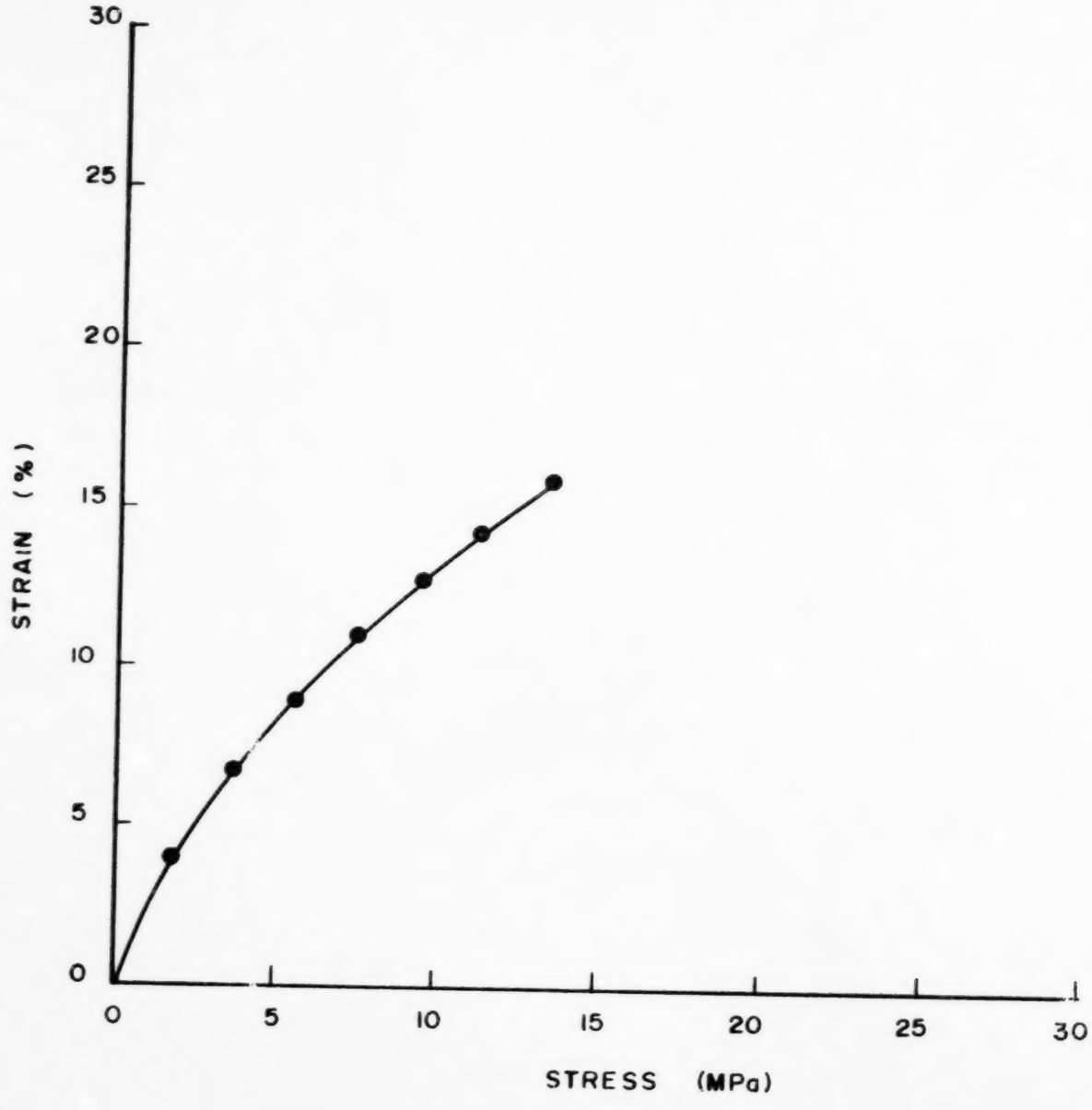

Figure A-25. Quasi-Static Consolidation Test Number T 09

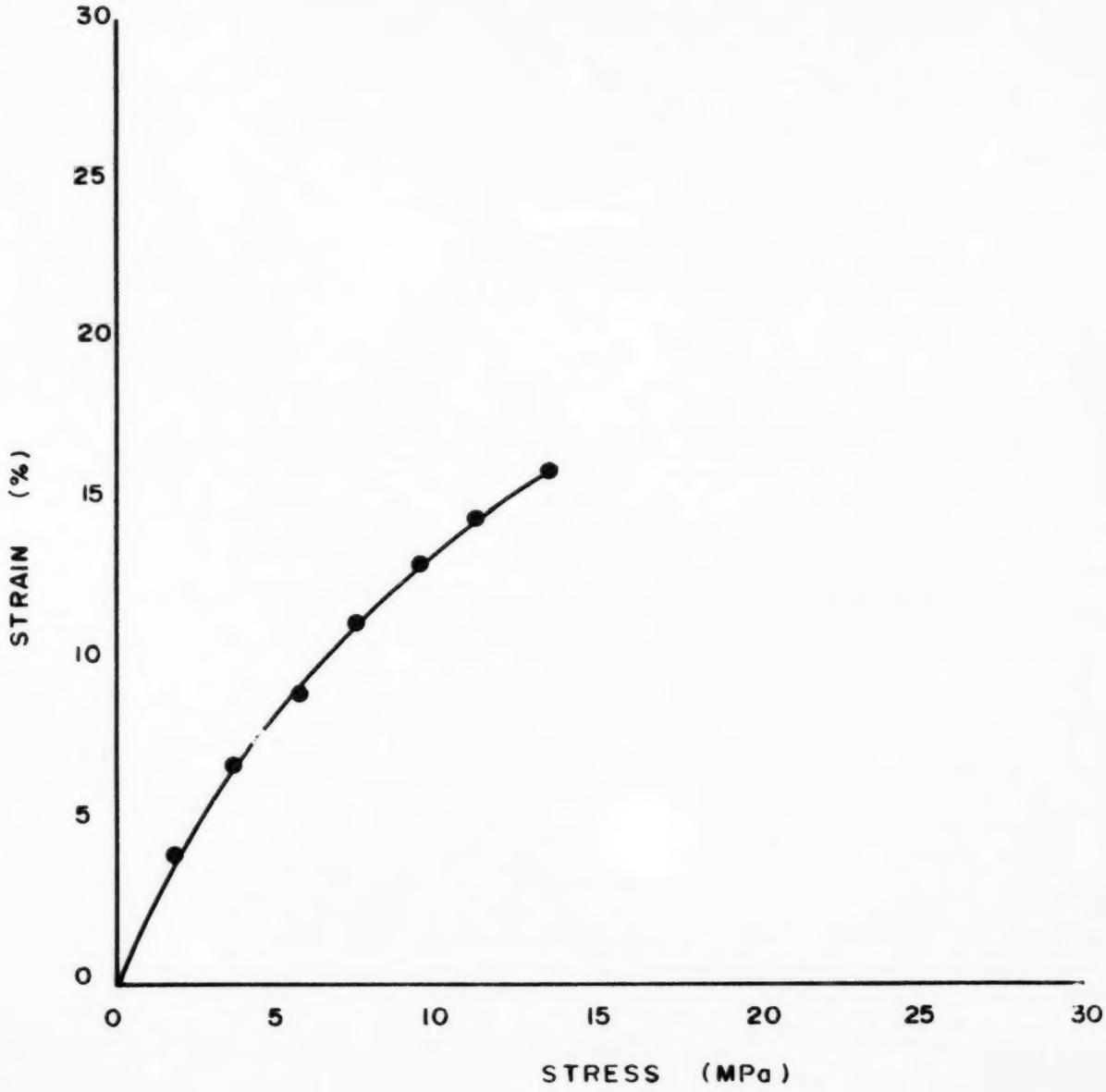

Figure A-26. Quasi-Static Consolidation Test Number T 10

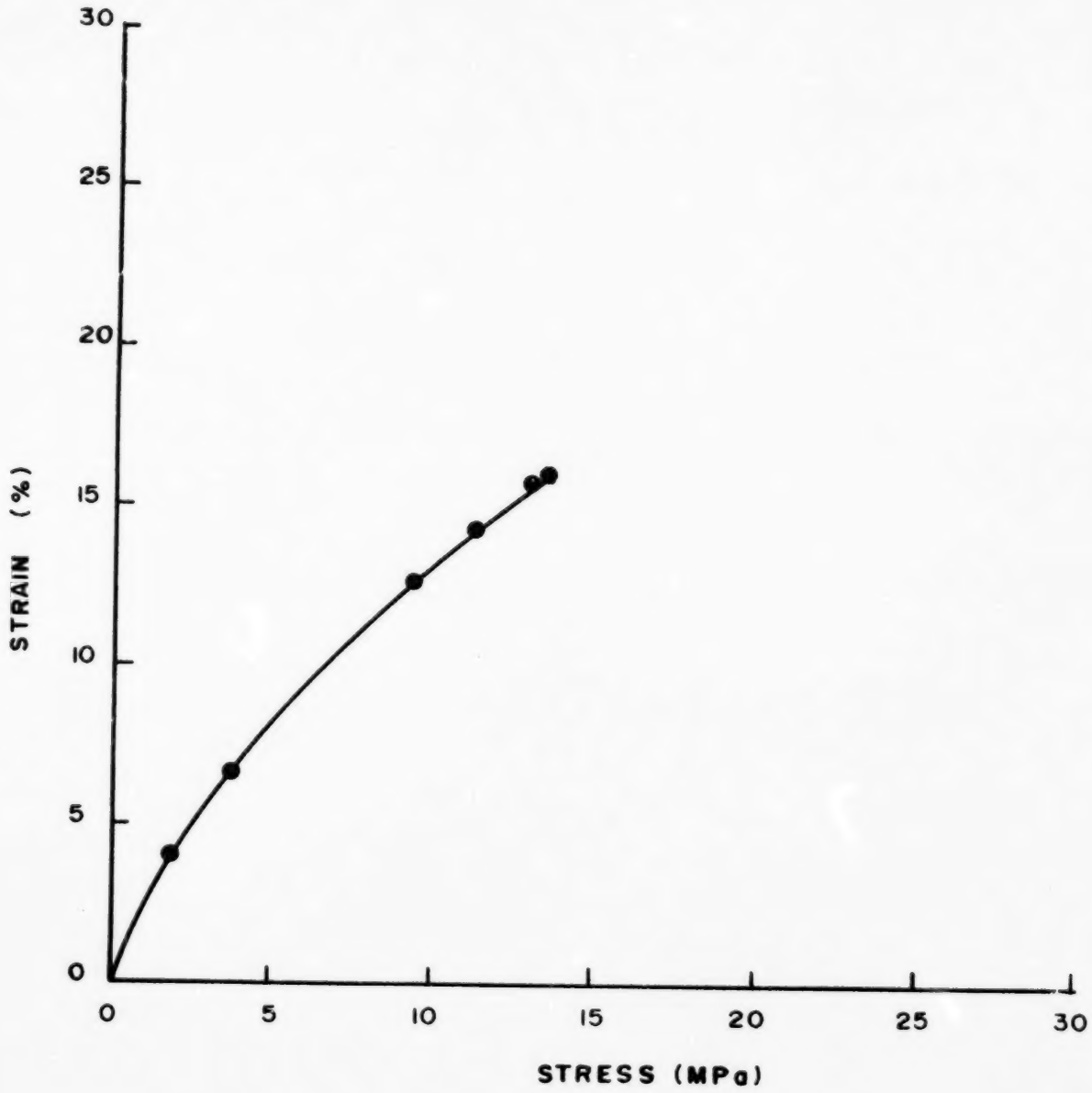

Figure A-27. Quasi-Static Consolidation Test Number T 11

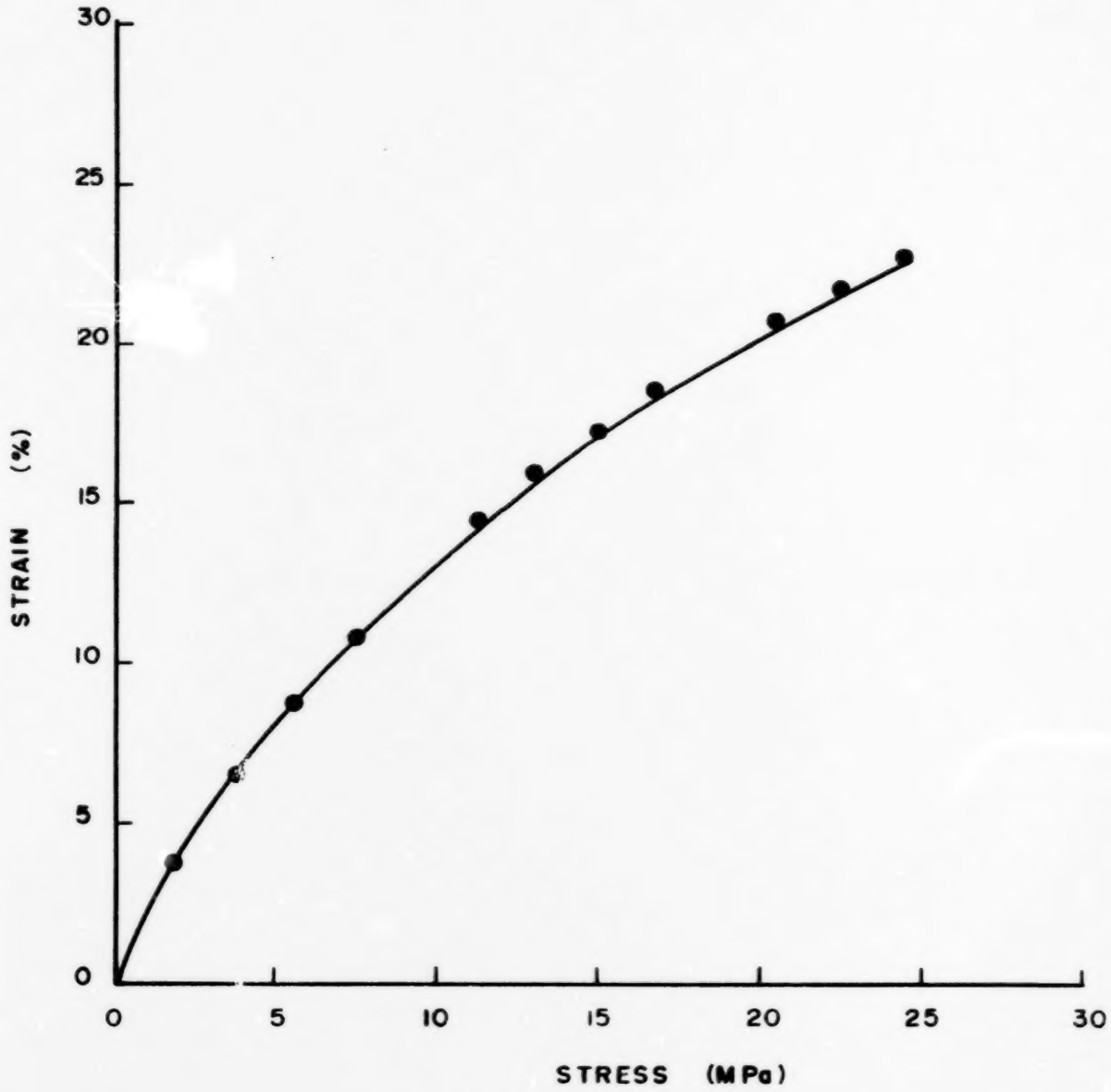

Figure A-28. Quasi-Static Consolidation Test Number C 01

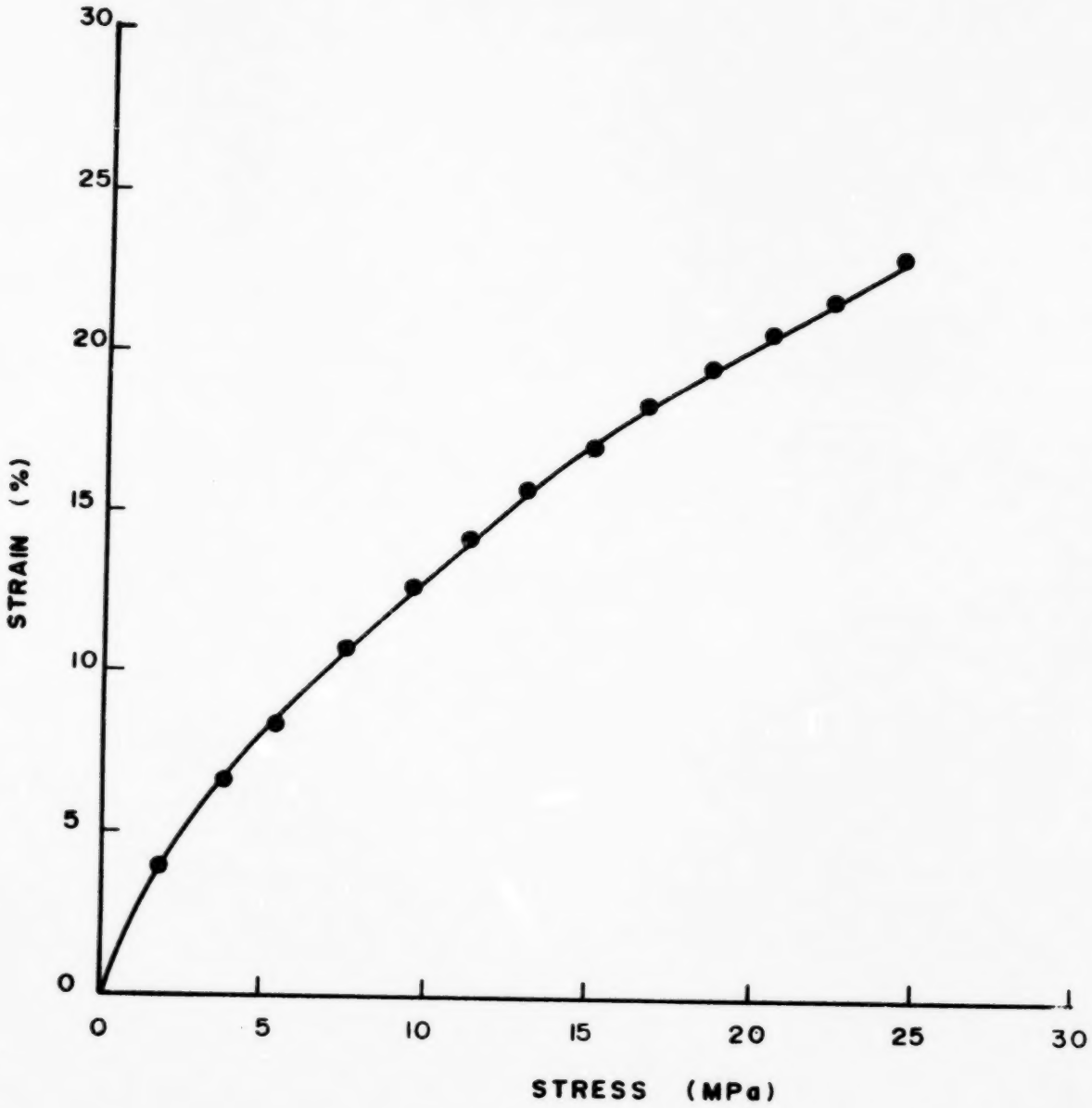

Figure A-29. Quasi-Static Consolidation Test Number C 02

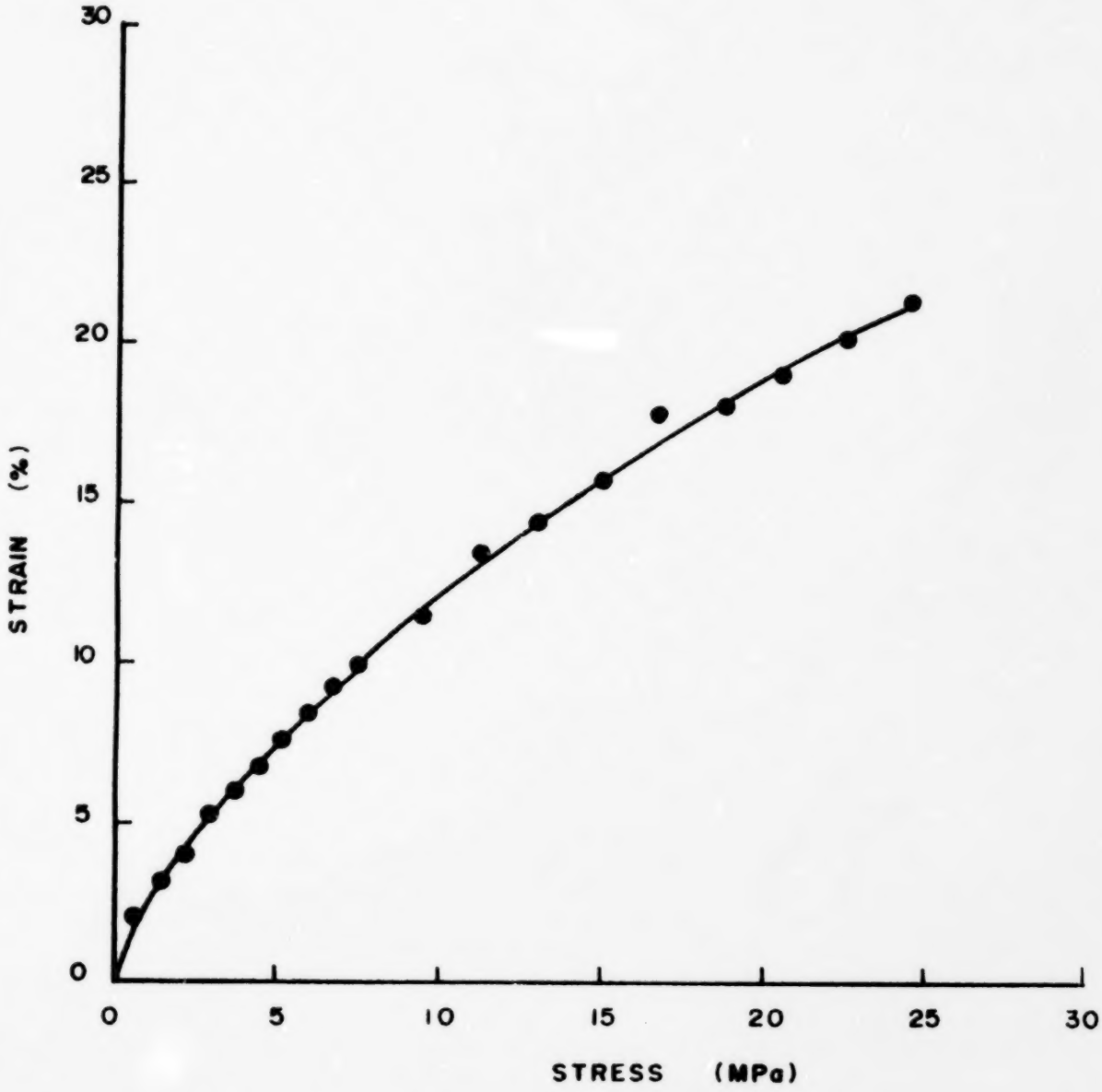

Figure A-30. Quasi-Static Consolidation Test Number C 03